PMSE System Operation in the 800 MHz LTE Duplex Gap

Findings from the coexistence measurements in Ispra,
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Authors: **D. Fuehrer, J. Fortuny-Guasch, C. Armiens Aparicio, J.-M. Chareau**

Joint Research Centre of the European Commission,
Institute for the Protection and Security of the Citizen (IPSC)

Via Enrico Fermi, 2749

I-21027 Ispra (VA)

Italy

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Summary

In this report the results of a study of a possible coexistence scenario for professional wireless audio systems, commonly referred to as PMSE (Programme Making and Special Events) systems, and broadband Mobile and Fixed Communication Networks (MFCN) are presented.

In the course of spectrum harmonization for the digital dividend in the European Union spectrum previously used by PMSE services was reassigned so that new spectrum suitable for these services had to be found. CEPT identified the bands 821-832 MHz and 1785-1805 MHz as potential candidates and defined technical conditions for the operation of PMSE in these bands which represent duplex gaps in existing LTE FDD systems.

Conditions for the coexistence of LTE and PMSE operating in the LTE duplex gap had been studied by a number of parties, with rather diverging results. On request of DG CNECT the JRC performed an analysis of the various studies and their discrepancies. Subsequently, DG CNECT suggested the deployment of LTE small cells in combination with LTE inter-band handover as a potential means to avoid or reduce interference from LTE to PMSE and requested the JRC to study the feasibility of this approach.

Using small cells might prevent harmful interference in indoor scenarios (e.g. theatres, musicals and live performances), which were identified as the most critical cases in terms of interference when LTE equipment and wireless audio PMSE equipment operate in close proximity. The basic idea is to steer away LTE uplink (terminal) traffic from the 832-862 MHz band (used in the macro cell) to the 2.6 GHz band (used in the small cell) and thus prevent adjacent channel interference to PMSE systems operating in the 821-832 MHz band (commonly referred to as the LTE duplex gap).

In response to the request from DG CNECT the JRC arranged a measurement campaign at its Ispra premises in November 2013, involving stakeholders from the PMSE community, mobile operators, and test equipment manufacturers. During four days, various PMSE systems and LTE terminals were tested and several Terabytes of measurement data were recorded. Preliminary results were presented at the RSC meeting #46 in December 2013. Observations made during the tests and the initial analysis of the measurement data confirmed that LTE Out-of-Band (OBB) interference can negatively affect the performance of both analogue and digital PMSE systems operating in the 800 MHz LTE duplex gap, with OBB emissions varying significantly between LTE User Equipment (UE) models.

An analysis of the inter-band handover process showed that if the handover from the 800 MHz band to the 2.6 GHz band was executed at a sufficiently early stage, i.e. before the LTE UE came too close to PMSE receiver, no harmful interference in the LTE duplex gap could be observed.

During the start-up test, i.e. when the LTE UE - while being within the coverage area of a local 2.6 GHz small cell and a distant 800 MHz macro cell - was switched on in close distance from the PMSE receiver, it was found that the LTE UE reliably connected to the LTE small cell base station, and no harmful interference in the 821-832 MHz duplex gap could be observed during the entire connection process.

The conclusion from the results of the LTE – PMSE coexistence measurements is that from a technical standpoint the use of LTE small cells in combination with inter-band handover can protect PMSE systems operating in the 800 MHz duplex gap. It is hypothesized that this conclusion will also hold for the 1800 MHz duplex gap.

Introduction

This report addresses the potential use of the 821-832 MHz band by Programme Making and Special Events (PMSE) equipment and specifically by wireless audio systems.

The 821-832 MHz band is generally referred to as 'LTE duplex gap' because it separates the downlink (DL) and uplink (UL) channels of LTE band no. 20 (further on referred to as the 800 MHz band). Wireless microphone channels typically occupy a bandwidth of up to 200 kHz for analogue systems [1] and 600 kHz for digital systems [2] so that in theory up to 55, resp. 18 such channels could fit into the duplex gap. Due to intermodulation effects, however, the actual number of usable channels is considerably lower.

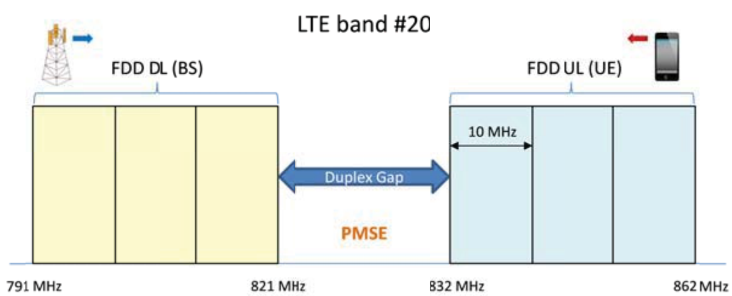

Figure 1: Concept of PMSE system operation in the 800 MHz LTE duplex gap

Technical conditions for the use of the 790-862 MHz range, and specifically of the 821-832 MHz LTE duplex gap by wireless microphones have been defined in decision ECC/DEC(09)03 [8] of the European Communications Committee (ECC) and Report 50 [3] of the European Conference of Postal and Telecommunications Administrations (CEPT).

Nevertheless, the suitability of these bands for PMSE was and still is controversially discussed because of the out-of-band (OOB) emissions from LTE base stations (BS) and user equipment (UE) that might create interference to PMSE receivers.

Previous studies

In 2012 and 2013 a number of studies were conducted with the objective to identify potential interference conditions and to quantify protection criteria for PMSE systems.

Measurements were conducted by the German Institut fuer Rundfunktechnik (IRT) [4], the Association of Professional Wireless Production Technologies (APWPT) [5], the Norwegian Post and Telecommunications Authority [6], the German Bundesnetzagentur (BNetzA) [7], and the United Kingdom's Ofcom [8] [9].

While all studies concluded that a potential for interference from LTE to PMSE systems exists, originating particularly from LTE UE, there was no consensus on the severity of the interference and the resulting protection criteria, owing to the lack of a common set of assumptions.

Interference avoidance through LTE inter-band handover

In July 2013, DG CNECT suggested to the JRC to evaluate a technical solution that might potentially resolve the interference issue by dynamically transferring LTE connections from the 800 MHz band to a different frequency range sufficiently distant from the 821-832 MHz duplex gap, namely the 2500-2690 MHz band (LTE band no. 7, further on referred to as the 2.6 GHz band). Local coverage in this band would be provided by one or more small cells.

Small cells come in a number of variants (Table 1) which address different deployment needs. Dense deployments in locations such as concert halls, theatres, and stadiums are typically realised with pico and femto cells. The capacity values provide below are indicative and based on industry estimates. The actual number of users that can be served within a cell depends on the type of services to be offered (which determines the bandwidth allocated to each user) and on the RF characteristics of the location such as interference and propagation conditions.

Cell type	**Typical cell radius**	**Transmit power range & Typical value**	**Deployment location**	**Capacity (no. of users)**
Macro	>1 km	20 W - 160 W (40 W)	Outdoor	>256
Micro	250 m - 1 km	2 W - 20 W (5 W)	Outdoor	64 - 256
Pico	<100 m	100 mW - 250 mW	Indoor	16 - 64
	100 m - 300 m	1 W - 5 W	Outdoor	16 - 64
Femto	10 m - 50 m	10 mW - 250 mW	Indoor	8 - 16
		200 mW - 1 W	Outdoor	8 - 32

Table 1: Typical LTE cell types and their characteristics [10] [11]

I should be mentioned that a potential alternative to small cells comes in the form of distributed antenna systems (DAS) which can be deployed indoors but are part of the macro network. A description of the DAS concept can be found in [12]. A second alternative could be Local IP Access (LIPA). Introduced in 3GPP rel. 9 and defined in 3GPP TR 23.829 [13], LIPA provides seamless interworking between LTE and WiFi. Data traffic can be offloaded to WiFi while time-critical services, such as VoIP continue to be delivered via LTE.

Within the scope of this report the actual implementation of the small cell network is of secondary importance. For reasons of simplicity the terms “picocell” and “pico base station” will be used further on in the text whenever a reference to small cells is made.

In the current coexistence scenario which has been thoroughly evaluated in the aforementioned studies, an LTE UE operates close to a PMSE receiver while being connected to a remote LTE macro BS (Figure 2). The attenuation of the signal path typically is high, due to distance, building loss, and other factors so that the LTE UE transmits at high power. Consequently, the level of the LTE signal received by the PMSE receiver is high, as well. As a result, the signal of the wireless microphone may be interfered.

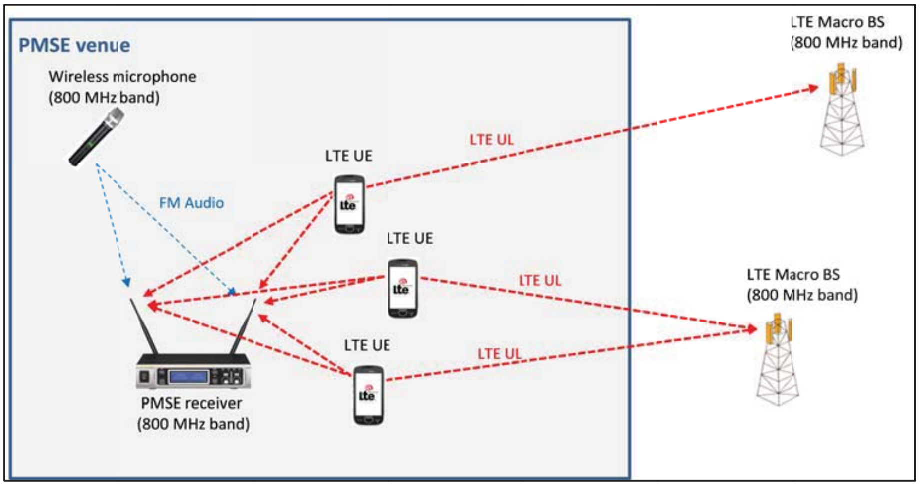

Figure 2: Current PMSE-LTE coexistence scenario

In the proposed scenario, a LTE pico BS would be set up in the vicinity of the PMSE receiver. An LTE UE located in the area of the PMSE receiver would receive a weak signal from the macro BS and a considerably stronger signal from the pico BS. Before generating interference at the PMSE receiver the LTE UE would have connected to the pico BS in the 2.6 GHz band and evacuated the critical 800 MHz band (Figure 3).

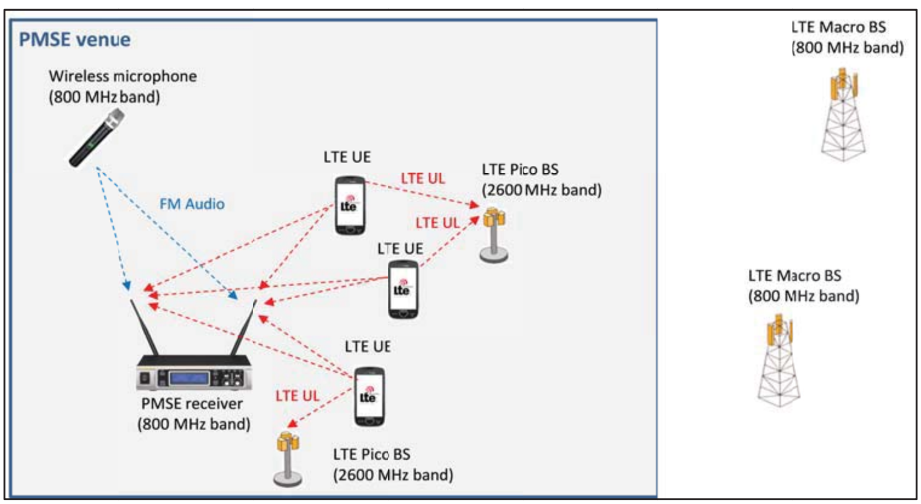

Figure 3: Potential future PMSE-LTE coexistence scenario

Evaluation - Test and measurement event

To evaluate whether the deployment of LTE picocells operating in the 2.6 GHz band can protect PMSE systems operating in the 821 - 832 MHz LTE duplex gap a test and measurement event with industry experts was organised by the JRC.

The measurements were conducted between November 13 and 15, 2013 at the JRC premises in Ispra, Italy. Among the participants were representatives of leading PMSE manufacturers AKG, Sennheiser, and Shure, the APWPT, the GSM Association (GSMA), test equipment manufacturers, and the JRC.

Test Cases

For the measurements two test cases were considered, the “In-operation” case and the “Start-up” case. A third test case to evaluate potential interference effects caused by intermodulation was added on request of the APWPT.

1. In operation

This test case simulated an LTE UE operating in the 800 MHz band that approached the PMSE receiver and LTE pico BS while transmitting data to a macro BS. The test was conducted in two steps:

In step 1 the impact of LTE UL OOB emissions on PMSE systems operating at various frequencies within the LTE duplex gap was determined. There was no LTE handover.

In step 2 a handover of the LTE connection from the 800 MHz band to the 2.6 GHz band was initiated at a certain point in time. The detailed scenario is as follows:

- A PMSE system consisting of a wireless microphone and a receiver is operating in the 821-832 MHz LTE duplex gap.
- An LTE macro BS operating in the 800 MHz band (LTE band 20) is located outside the venue.
- An LTE pico BS operating in the 2.6 GHz band (LTE band 7) is located in the vicinity of the PMSE receiver.
- In a distance d_1 from the PMSE receiver an LTE UE operating in the 800 MHz band is uploading data to the network via the macro BS.
- While connected to the LTE macro BS, the LTE UE moves towards the PMSE receiver and the LTE pico BS up to a minimum distance of $d_{2,\,min}$ and $d_{3,\,min}$, resp.
- At a certain distance d_3, which corresponds to a predefined LTE transmit power level received by the LTE pico BS, the LTE UE connection is transferred from the macro BS to the pico BS while the LTE UE continues uploading data to the network.

The threshold value at which the handover occurred was variable.

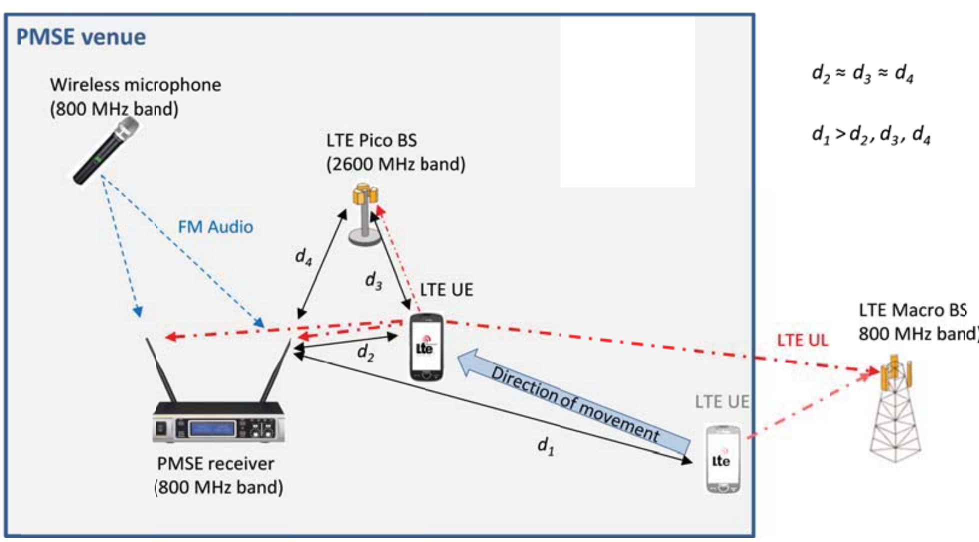

Figure 4: In-operation case

2. Start-up

In the start-up case a multi-band LTE UE was switched on nearby a PMSE receiver and an LTE pico BS. The detailed scenario is as follows:

- A PMSE system consisting of wireless microphone and receiver is operating in the 821-832 MHz LTE duplex gap.
- An LTE UE is located in a distance d_1 from the PMSE receiver. The LTE UE is off.
- An LTE pico BS operating in the 2.6 GHz band is located in the vicinity of the PMSE receiver, in a distance d_2 from the LTE UE.
- An LTE macro BS operating in the 800 MHz band is located outside the venue, in a distance d_3 from the LTE UE. d_3 is significantly larger than d_2 so that at the location of the LTE UE the signal from the LTE pico BS is stronger than that of the macro BS.
- The LTE UE is switched on. After scanning its environment it should eventually register with the pico BS.

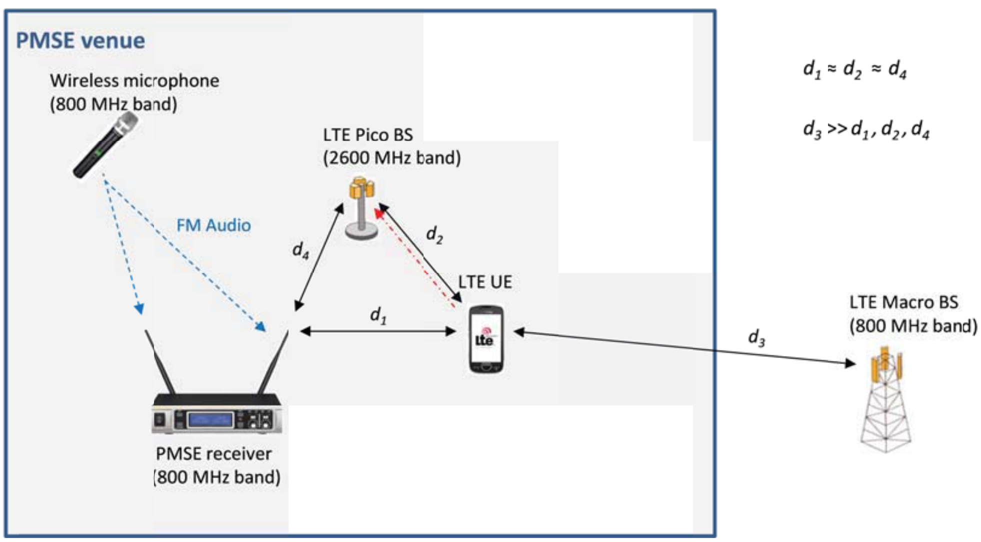

Figure 5: Start-up case

3. Dual-band PMSE

In this scenario two PMSE systems were operating simultaneously, one in the 821-832 MHz band and the other in the 1800 MHz band. An LTE UE operating in the vicinity of both PMSE receivers was repeatedly transferred from the 800 MHz band to the 2.6 GHz band and back. The detailed scenario is as follows:

- A PMSE system (wireless microphone and receiver) is operating in the 821-832 MHz LTE duplex gap.
- At the same time a second PMSE system is operating in the 1800 MHz band.
- An LTE macro BS operating in the 800MHz band is located outside the venue.
- An LTE pico BS operating in the 2600MHz band is located in the vicinity of both PMSE receivers.
- An LTE UE operating in the 800MHz band is located in a close distance from both PMSE receivers.
- The LTE UE is repeatedly transferred from the 800 MHz band to the 2.6 GHz band and back..
- The audio signal of the 1800 MHz PMSE systems is monitored for interference.

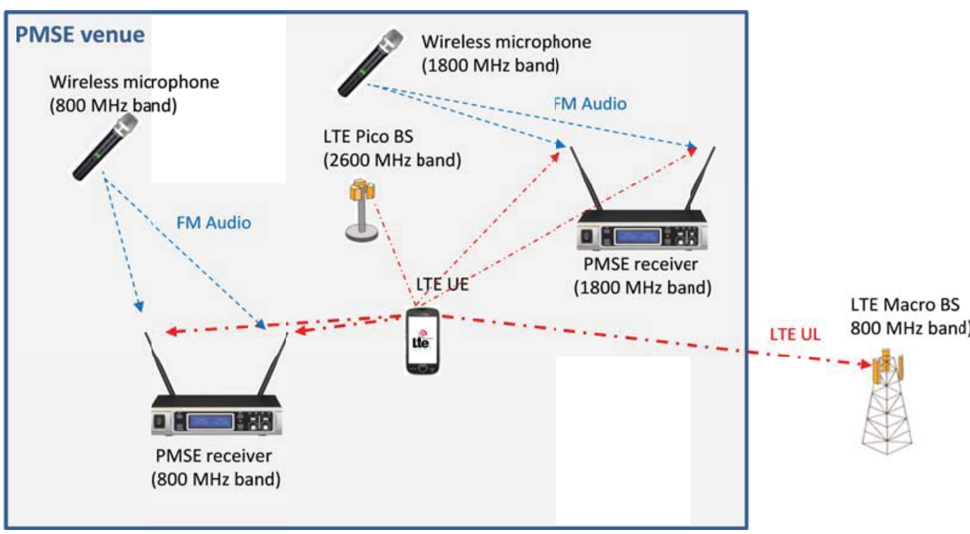

Figure 6: LTE UE transmitting in the vicinity of two PMSE systems operating in the 800 MHz and 1800 MHz bands

Test Setup

In order to reduce unwanted/uncontrollable interference effects and to make results more easily comparable with those of previous studies the measurements were performed in conducted mode.

The most critical elements of the setup were the LTE macro and pico base stations. While there had been several options for realising the LTE base station functionality it was eventually decided to use the R&S CMW500 LTE BS emulator, for the following reasons:

- Established and recognised LTE test platform.
- Full control of network parameters.
- Support for multi-network handover.
- Two independent networks can be emulated with one unit.
- Conducted tests are possible.
- Already used in the APWPT/IRT measurements. UL traffic configuration exists.
- Results can easily be compared to those of the IRT measurements.

In order to create a realistic interference scenario commercially available LTE USB modems and smartphones were used for LTE UE.

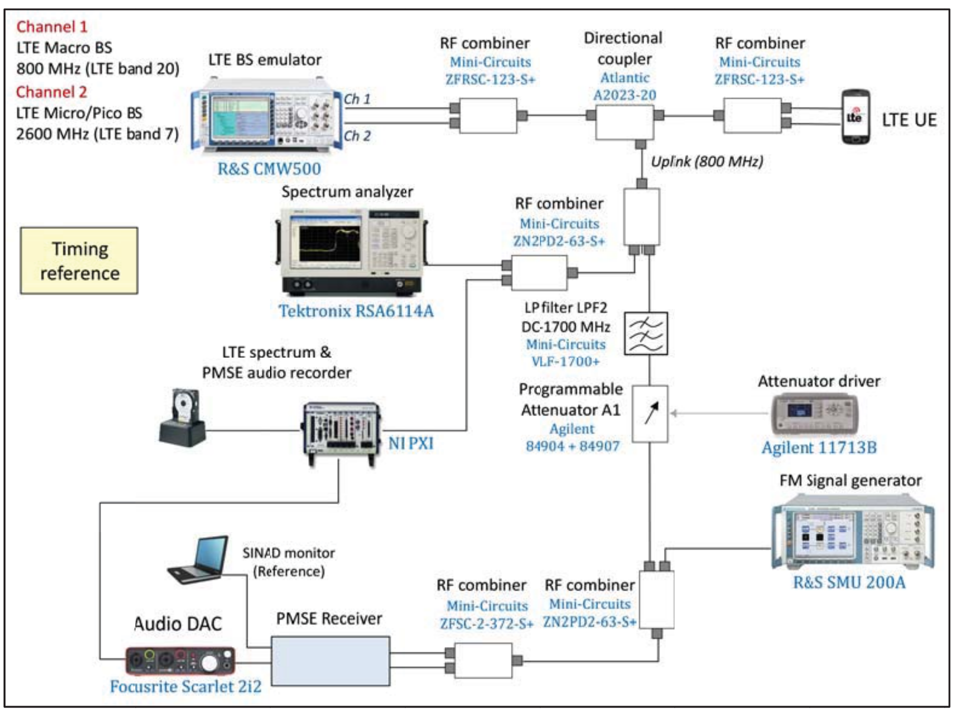

Figure 7: Test setup for analogue PMSE systems and LTE UE with antenna connectors

The LTE UE was connected with both base stations via two RF combiners and a directional coupler. The attenuation on these paths was maintained constant during the measurements. Initially, it had been foreseen to simulate an LTE UE moving towards both PMSE receiver and pico BS which would have required varying the path attenuation between LTE UE and LTE pico BS. This variation, however, caused the connection between LTE UE and pico BS to become unstable; for this reason the above setup was adopted.

As the LTE uplink (UL) signal is the major cause of interference within the LTE duplex gap this signal was coupled out via a directional coupler. It was then distributed to a spectrum analyser (for monitoring purposes), to the PXI (for analysis, display and recording), and to a 1700 MHz low-pass filter. The purpose of this filter was to isolate the PMSE receiver from the relatively high-power 2.6 GHz LTE signal. The filtered signal then entered a programmable attenuator (A1).

For the in-operation test the movement of the LTE UE towards the PMSE receiver was simulated with the help of this attenuator which covered the range from 0 to 81 dB in steps of 1 dB. At A1 = 0 dB the overall path attenuation between LTE UE and PMS receiver was 42 dB, corresponding to a line-of-sight (LOS) distance of 3.6 meters. The attenuation was controlled from a PC (not shown above) that also managed the LTE handover and the data recording processes and served as a timing reference for the other components of the test setup (BS emulator, spectrum analysers, signal generators, PCs).

Finally, the LTE UL signal was inserted into the PMSE signal path. When analogue PMSE receivers were tested, the PMSE test signal was generated by an R&S MU200A signal generator. The composite PMSE-LTE signal was then fed the PMSE receiver. It was found that the operational stability of some receivers was improved by connecting both antenna inputs. This setup was maintained throughout the measurements and applied to all receivers.

One of the PMSE receiver audio outputs was connected to a high-definition audio analogue-to-digital converter (ADC) whose output signal was fed into a National Instruments PXI system which served as a real time spectrum analyser, audio signal-to-noise-and-distortion-ratio (SINAD) analyser, signal monitor, RF signal analyser, and RF and audio data recorder.
The second audio output was connected to a notebook PC running the ComTekk SINAD analysis software [13]. The ComTekk software had been used in previous measurement such as the one at IRT [4] to determine SINAD reference levels.

> *SINAD is a parameter for measuring the quality of an audio signal originating from a communication device. For a radiocommunication system this is usually done by transmitting an FM signal modulated at 1 kHz and with a specified deviation to the receiver. At the receiver's audio output the 1 kHz tone plus noise and distortion products will be present.*
>
> *To measure the SINAD this audio signal is first passed through a filter which restricts the bandwidth of the signal to the important range around 1 kHz. In the ComTekk software a C-Message filter has been implemented. The filtered audio signal is measured and then passed through a notch filter which removes the 1 kHz tone. The resulting signal which consists of noise + distortion only is then measured and compared with the first measurement. The ratio is the SINAD value[1].*

For LTE UE without antenna connectors the modified test setup shown in Figure 8 was used. The LTE UE was placed in an RF test fixture (antenna coupler) whose output was connected to the directional coupler.

[1] Adapted from [18]

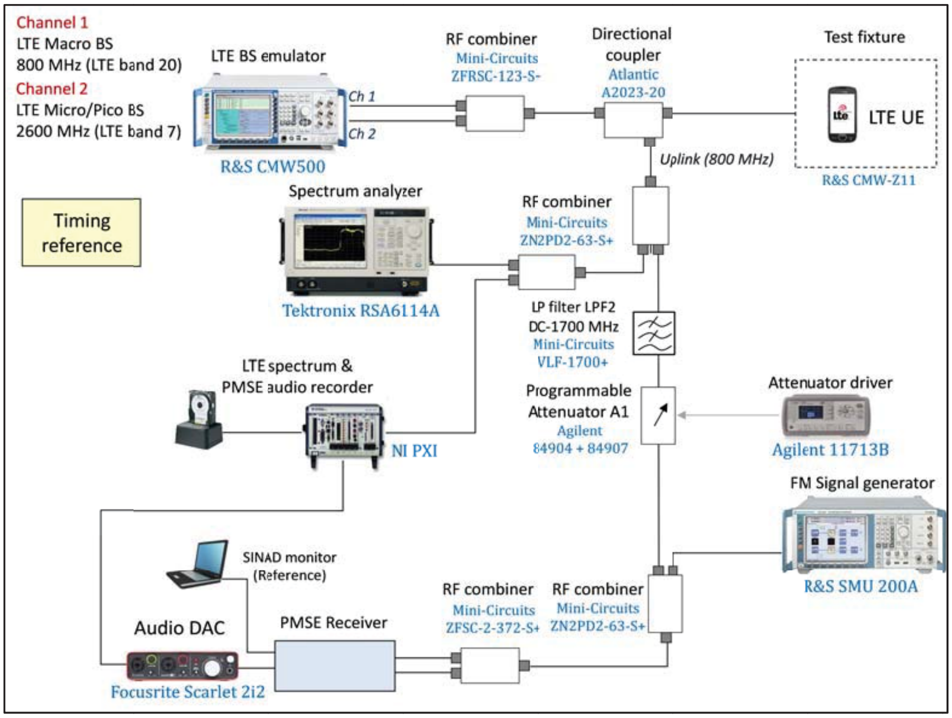

Figure 8: Test setup for analogue PMSE systems and LTE UE without antenna connectors

The digital PMSE systems that were tested used proprietary RF signals so that the test signal had to be generated by the respective PMSE transmitter. The test signal level was adjusted with variable attenuator A2. To avoid coupling from the transmitter's antennas into the PMSE receive path the transmitter was placed in an RF test fixture (Figure 9).

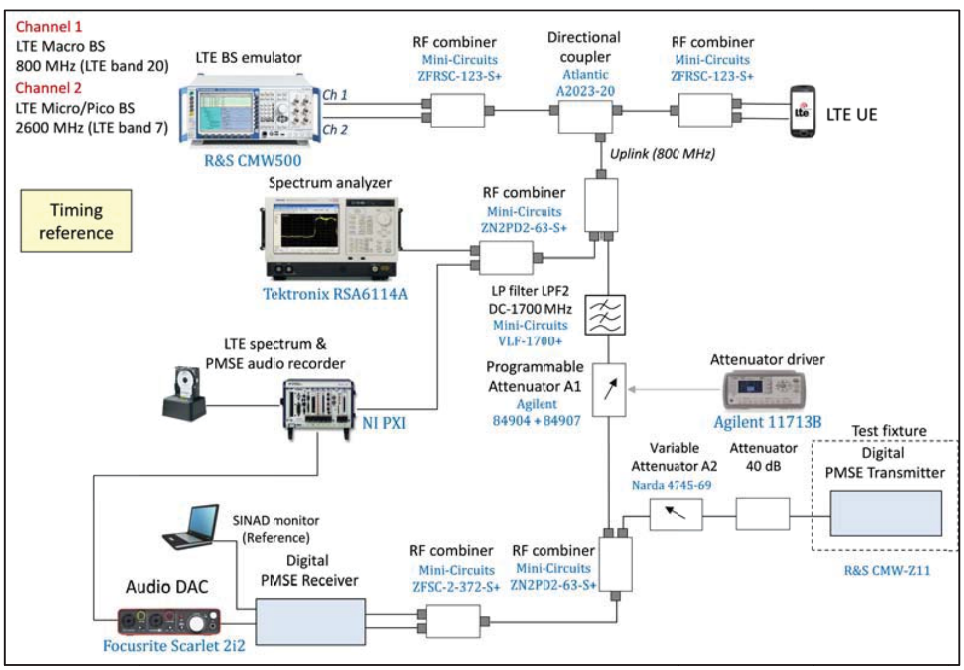

Figure 9: Test setup for digital PMSE systems

For the dual-band PMSE measurements an 1800 MHz signal generator and PMSE receiver were added to the PMSE signal path (Figure 10).

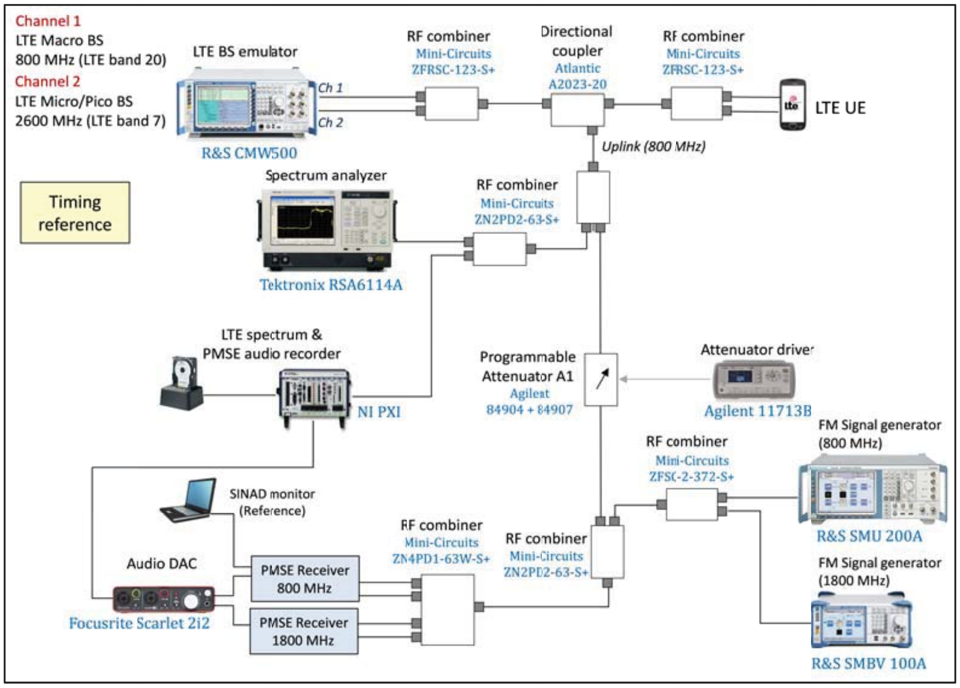

Figure 10: Test setup for dual-band analogue PMSE systems

Test automation and signal processing were done using National Instruments LabView.

Equipment tested

PMSE equipment

The following PMSE systems were tested:

Analogue (receiver only)

- AKG SR470
- Sennheiser EM3732-II
- Shure UR4D

Digital

- AKG DSR 700 + AKG digital transmitter
- Shure ULXD4Q + Shure digital transmitter

A fourth analogue PMSE receiver had technical issues and could therefore not be included in the measurements.

LTE user equipment

Seven commercially available LTE devices from major manufacturers were tested.

USB modems

- Huawei E3276
- ZTE 4G
- Vodafone
- Telekom (Huawei E398)

Smartphones

- LG E-975
- Sony Xperia Z
- Samsung Galaxy S4

Test Parameters

PMSE

The characteristics of the PMSE test signal were defined to match those used in previous measurement sessions, particularly the one conducted by the IRT [4]. Measurements were made at six carrier frequencies ranging from the edge to the centre of the duplex gap in steps of approx. 1 MHz. Because the set of frequencies had to be supported by all tested PMSE receivers the frequency spacing is not even.

- Carrier frequencies
  - 830.950 MHz
  - 830.100 MHz
  - 828.950 MHz
  - 827.950 MHz
  - 827.025 MHz
  - 825.925 MHz
- Deviation: 3 kHz (corresponding to a very 'silent' audio signal)
- Modulation: FM
- Modulation signal: 1 KHz sine wave

LTE

The CMW500 base station emulator used during the measurements featured two independent channels which were configured for operation the 800 MHz LTE band (band #20) and the 2.6 GHz band (band #7), resp. (Table 2).

CMW500 channel no.	1	2
Base station	Macro	Pico
LTE band	20	7
UL center frequency [MHz]	837	2535
Channel width [MHz]	10	10
Full cell bandwidth power [dBm]	-95	-42,2

Table 2: CMW500 basic configuration

In order to create a realistic scenario in which the macro BS DL signal experiences high attenuation due to distance and building loss the macro base station transmit power was set to a level significantly lower than that of the pico BS. At the same time LTE UE transmit (UL) power was maximised.

The uplink was configured to emulate a critical, and probably worst-case yet realistic scenario in which multiple LTE UE upload data to the network. The configuration (Figure 11) suggested by Technische Universitaet Braunschweig was used in the IRT measurements in June 2013.

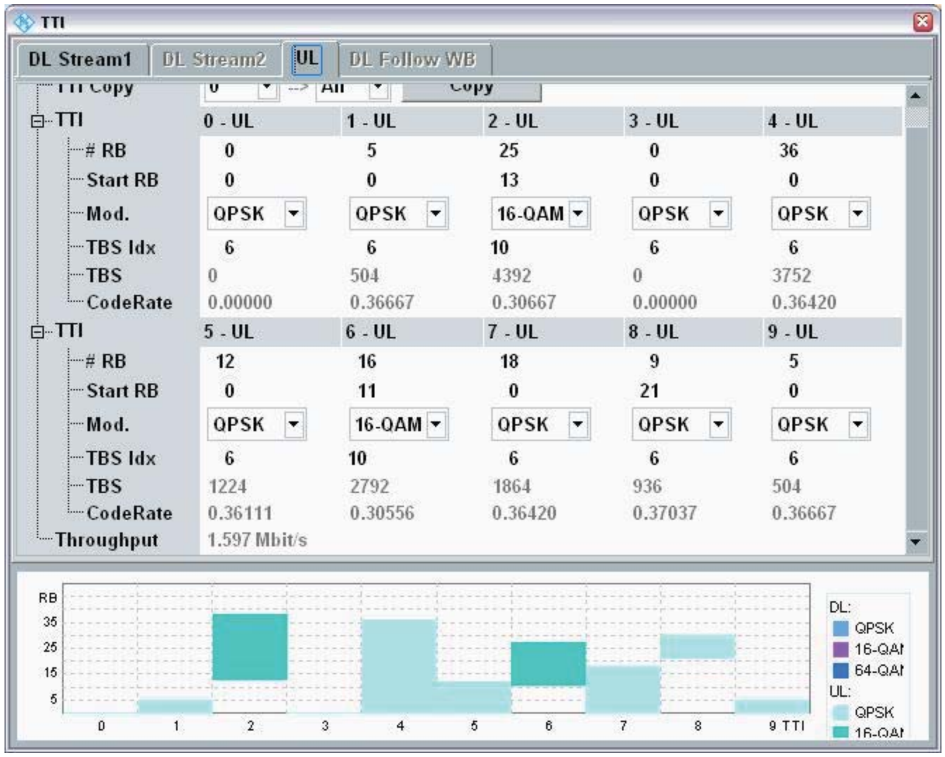

Figure 11: LTE uplink configuration

The duration of an LTE frame is 10 ms. One frame comprises 10 transmission time intervals (TTI) or subframes of 1 ms. For each TTI the number of resource blocks (RB), the position of the start RB, the modulation type, and the transport block size index (TBS Idx) can be configured. Each TTI was configured in a way that within one frame there was a combination of different modulations, resource blocks and offsets, and TBS indices. In addition, transmit power levels were varied according to the pattern shown in Figure 12.

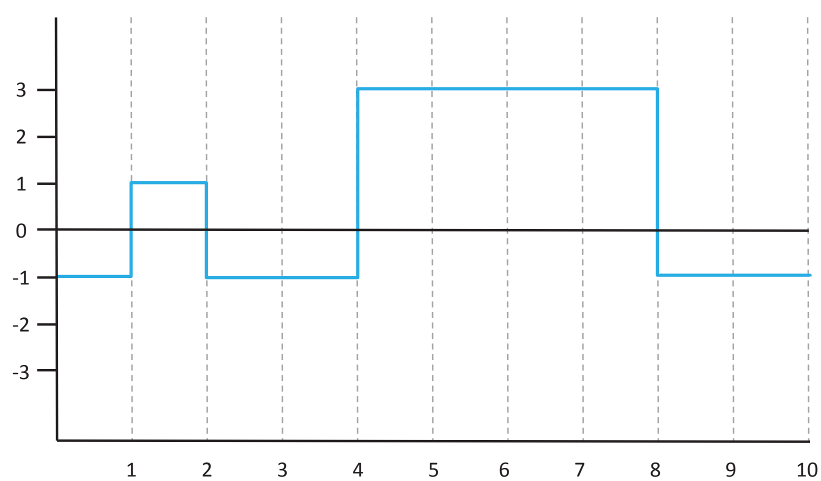

Figure 12: Uplink transmit power pattern

Measurements

In the first step, the transmit signal spectra of the various LTE UE were measured. The results were compared with those obtained in previous measurement campaigns and found to be consistent.

LTE UE uplink signal spectrum

The four tested USB modems produced OOB emissions of up to 30 dB above the noise level close to the LTE block edge, and up to 17 dB above the noise level and 827 MHz, 5 MHz below the LTE block edge. Between LTE devices, OOB emissions varied up to 10 dB.

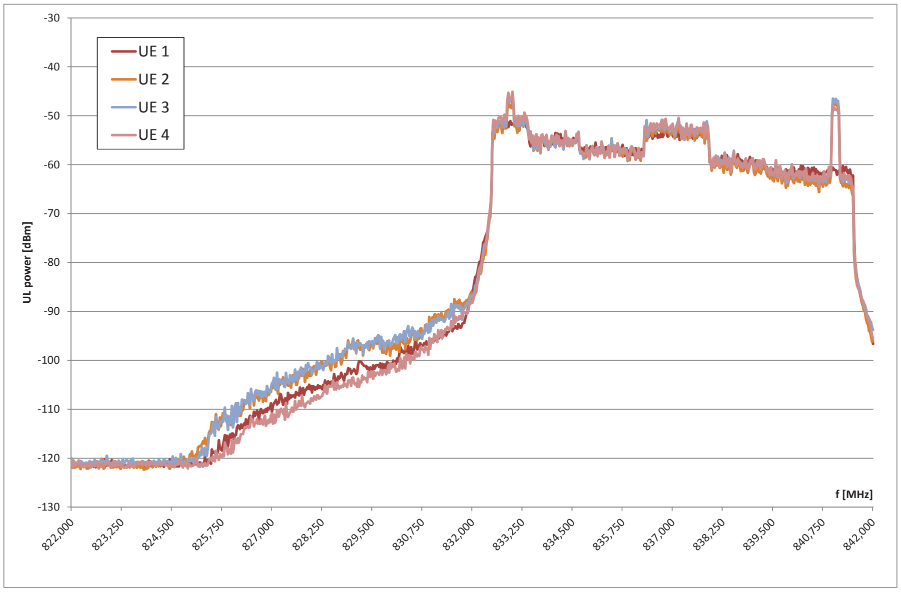

Figure 13: Comparison of the spectra and OOB emissions of the four tested LTE USB modems

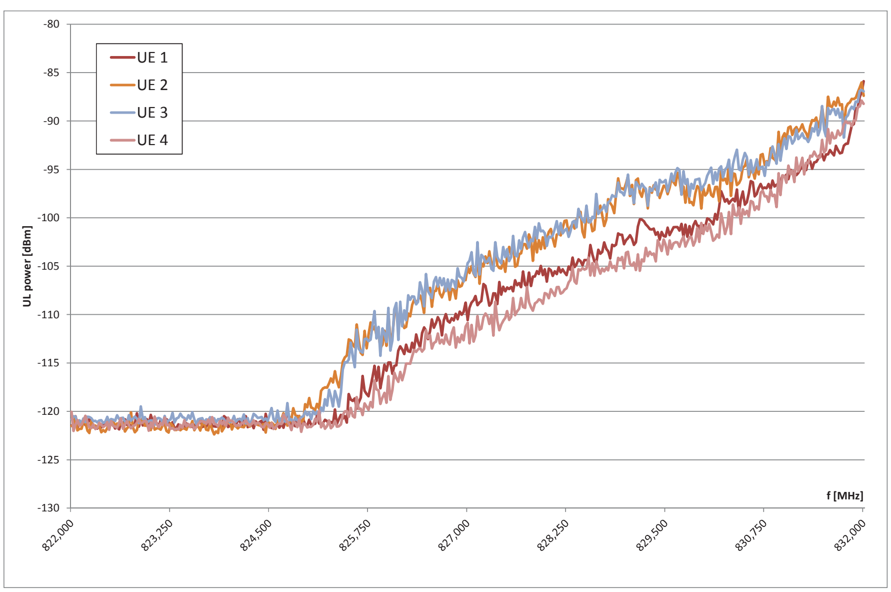

Figure 14: Comparison of the OOB emissions of the four tested LTE USB modems in the 822-832 MHz range

Two of the three tested smartphone showed similar OOB emission levels as the USB modems. Emissions of the third specimen were up to 10 dB lower.

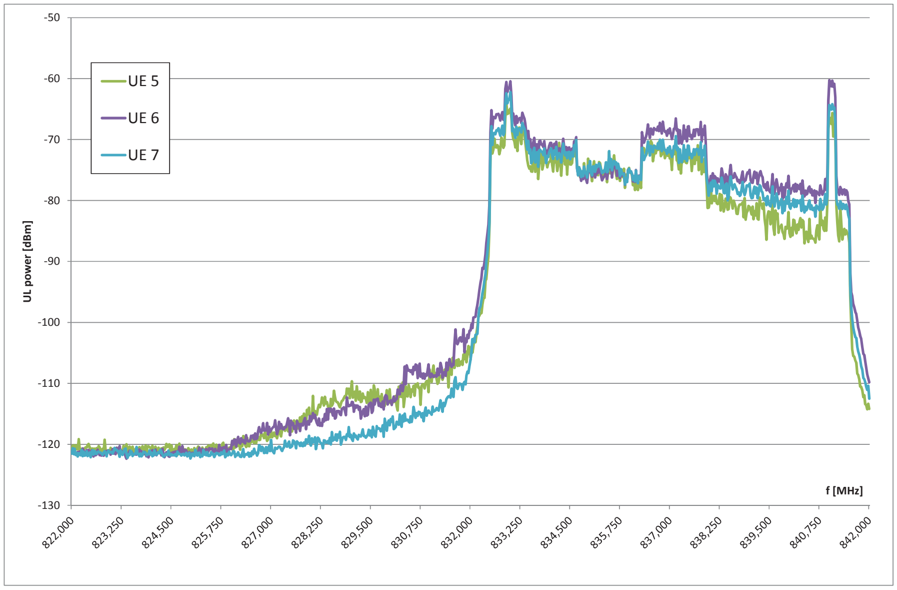

Figure 15: Comparison of the spectra and OOB emissions of the three tested LTE smartphones

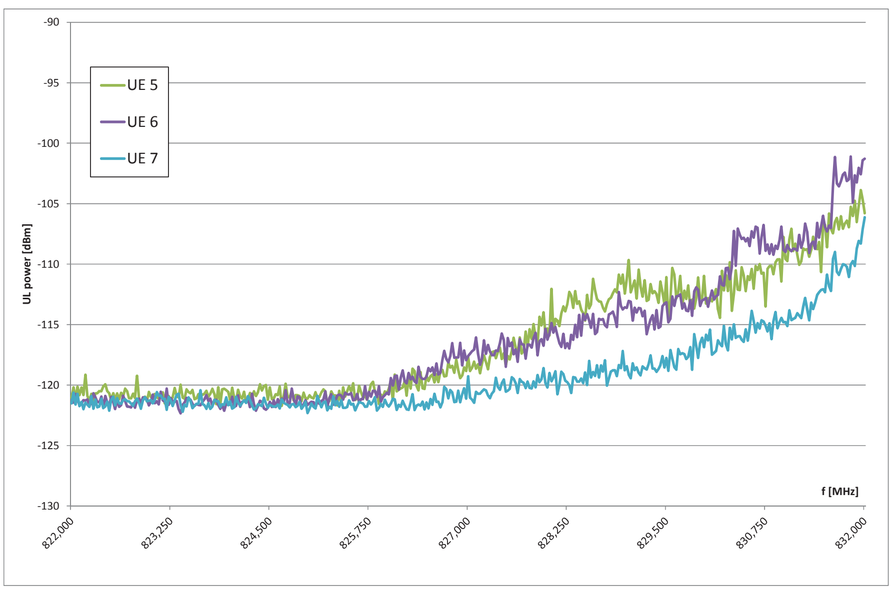

Figure 16: Comparison of the OOB emissions of the three tested LTE smartphones in the 822-832 MHz range

Note: In the smartphone measurements the dynamic range was reduced by 15 dB, compared to the USB modem measurements.

In-operation test

For the in-operation test the RF output power of the PMSE signal generator was adjusted so that for the analogue PMSE receivers an audio output SINAD of 30 dB was indicated by the ComTekk reference software. At this time the LTE signals were switched off. Depending on the receiver model sensitivity varied in the range of 8 dB (Table 3). For the two digital receivers matching digital transmitters had to be used whose RF signal levels were adjusted to obtain the nominal SINAD for 60 dB.

PMSE receiver model	PMSE receiver type	Sensitivity level [dBm]
A	Analogue	-101,8
B	Analogue	-94,3
C	Analogue	-102,3
D	Digital	-91,3
E	Digital	-92,3

Table 3: PMSE receiver sensitivity levels (30 dB SINAD)

According to ETSI [14] a SINAD of 30 dB constitutes the absolute minimum for professional applications. This assessment could be confirmed during the tests. At this SINAD level white noise and spikes (Figure 17) were observed which were audible as crackling and clicks. In a real operating scenario this low-level noise would be suppressed by the receivers' squelch function which was disabled during these measurements. As the determined SINAD value depends on the quality of the audio analogue to digital converter (ADC) the actual SINAD was even somewhat higher than 30 dB. Using identical test settings, SINAD values measured with the Focusrite Scarlet high-quality audio converter were 3 dB higher than those measured with the reference notebook PC.

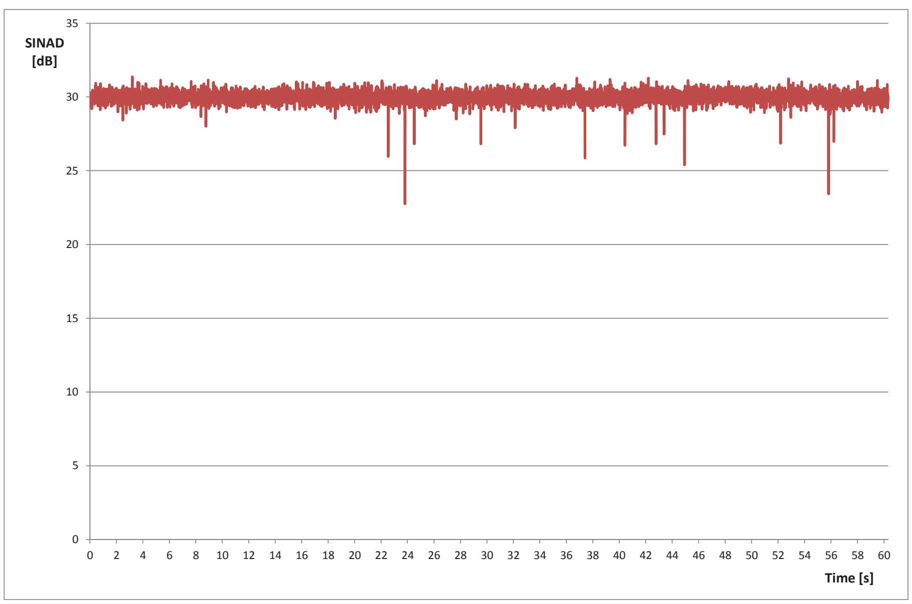

Figure 17: Analogue PMSE receiver audio output signal at 30 dB SINAD (resolution: 10 ms)

After the LTE macro BS and UE were switched on the overall attenuation between LTE UE and PMSE receiver was reduced from 102 dB to 42 dB in steps of 1 dB per second. In this way the movement of an LTE UE (or rather, multiple LTE UE, considering the UL signal pattern) towards the PMSE receiver was simulated. These parameters were calculated based on the ITU-R P.1238-7 non-line-of-sight (NLOS) path loss model [15] to simulate LTE UE approaching a PMSE receiver from a distance of 150 m down to 2 m, at an average speed of 2.4 m/s which corresponds to fast walking speed[2].

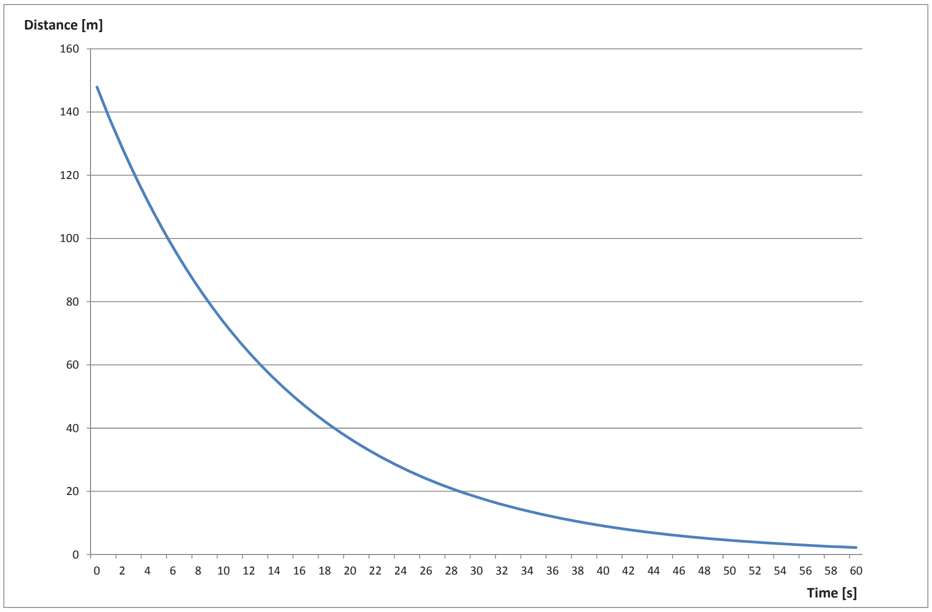

Figure 18: Simulated distance between LTE UE and PMSE receiver over time[2]

[2] The distance calculation is based on the ITU-R P.1238-7 indoor path loss model [12], office environment, transmitter and receiver located on the same floor

The impact of LTE uplink OOB emissions on PMSE signal quality

In the first part of the in-operation test the impact of LTE UE OOB emissions on the PMSE signal quality, i.e. the SINAD, was investigated. The separation between LTE UE and PMSE receiver was constantly reduced and the RF and PMSE receiver audio output signals were recorded. Measurements were conducted for combinations of four LTE UE and two analogue PMSE receivers with significantly different sensitivity levels. For each measurement, a SINAD deterioration point was determined which represents the attenuation value from which on the SINAD remained below 30 dB.

Figure 19 shows the SINAD curve plotted against the separation between LTE UE 2 and PMSE receiver A for the highest and lowest PMSE frequencies. In line with the LTE OOB interference levels measured previously the SINAD of the PMSE signal at 830.950 MHz, close to the LTE block edge, decreases significantly earlier than that of an 825.925 MHz signal. The difference in this case is approximately 26 dB.

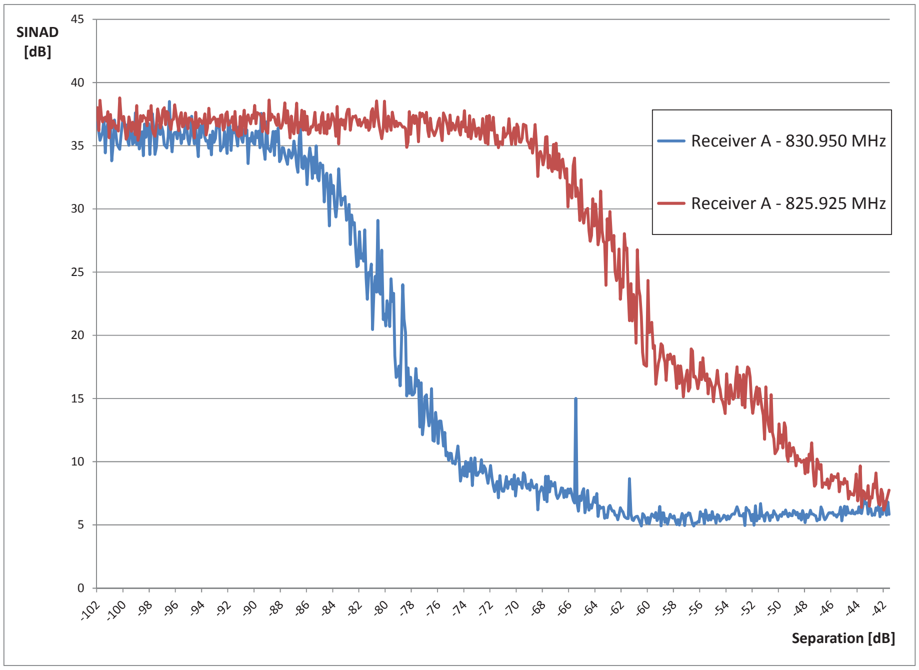

Figure 19: PMSE SINAD vs. separation between LTE UE #2 and PMSE receiver A

In Figure 20 the SINAD curves for two PMSE receivers with different sensitivities are depicted. At both frequencies the SINAD of the more sensitive receiver (Receiver A) decreases earlier than that of the less sensitive system. The difference in both cases is about 8 dB, in line with the difference in sensitivity measured earlier.

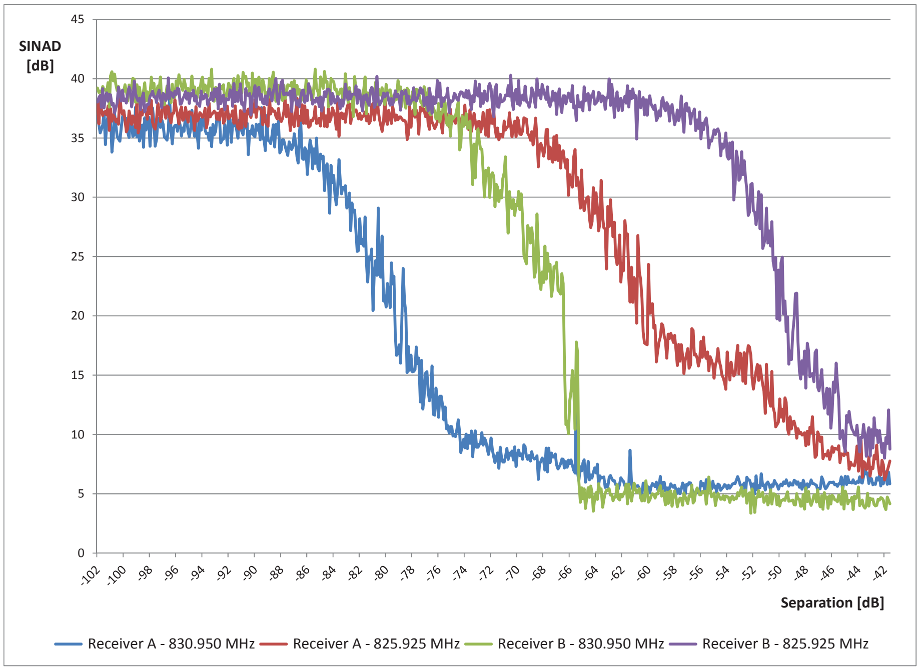

Figure 20: SINAD vs. separation between LTE UE and PMSE receiver for different analogue receiver models

The two digital receivers displayed a slightly different behaviour which is typical for digital systems. At high separation values the SINAD was varying considerably (up to 10 dB) but always remained above 35 dB. From a certain separation on the SINAD suddenly dropped to zero, recovered briefly, and dropped to zero again (Figure **21**).

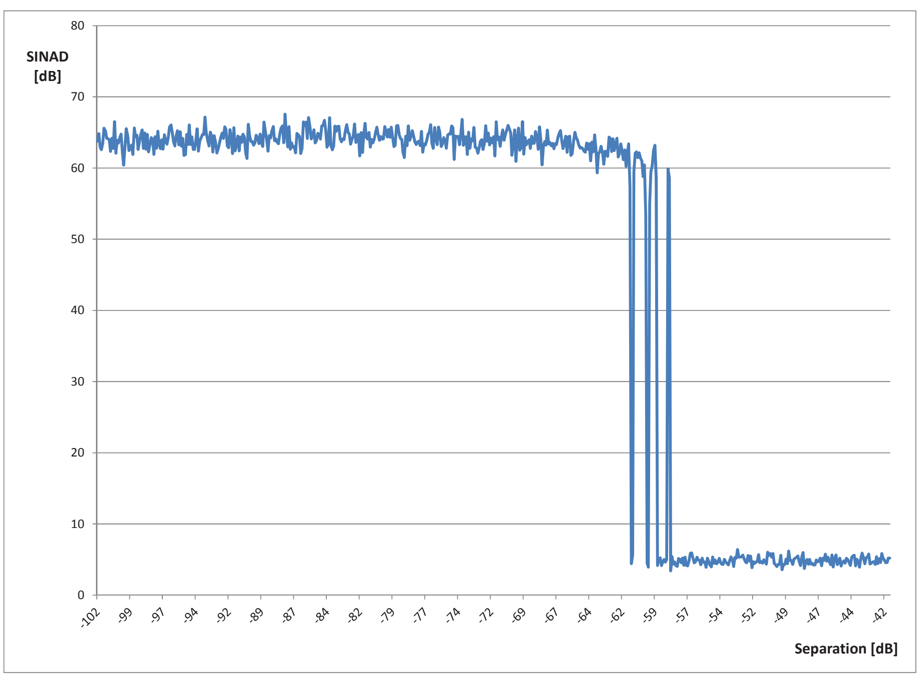

Figure 21: SINAD of digital PMSE receiver D vs. separation (at 825.925 MHz)

For sixteen combinations of LTE UE, PMSE receiver and PMSE frequencies the SINAD deterioration points which correspond to the minimum separation distances between LTE UE and PMSE receiver were determined (Figure 22). At a PMSE frequency of 825.925 MHz the minimum separation ranged from 68 dB to 76 dB, while at 830.950 MHz the minimum separation was 84 dB to 97 dB.

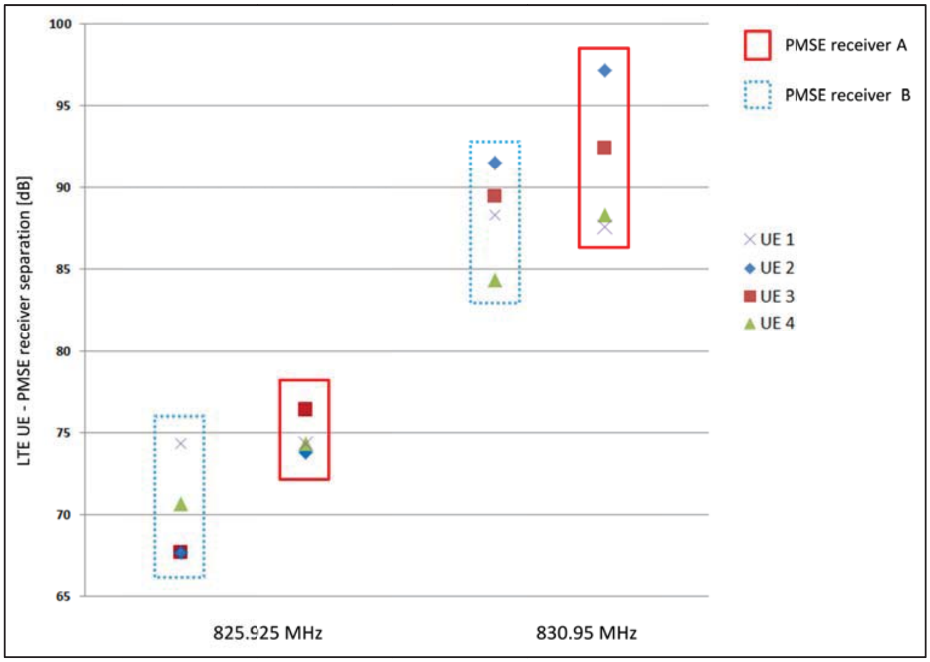

Figure 22: Distribution of SINAD deterioration points for different LTE UEs

SINAD deterioration points were also determined for all five PMSE receivers in combination with the most critical (in terms of OOB interference) LTE UE. At a PMSE frequency of 825.925 MHz the minimum separation ranged from 56 dB to 77 dB, while at 830.950 MHz the minimum separation was 81 dB to 97 dB. Separation values for the two digital systems (receiver models D and E) were lower (between 4 dB and 21 dB) than for the analogue ones. The results for analogue and digital receivers are not directly comparable because the reference metrics for determining the minimum sensitivity level were different (SINAD for the analogue systems and SNR for the digital systems).

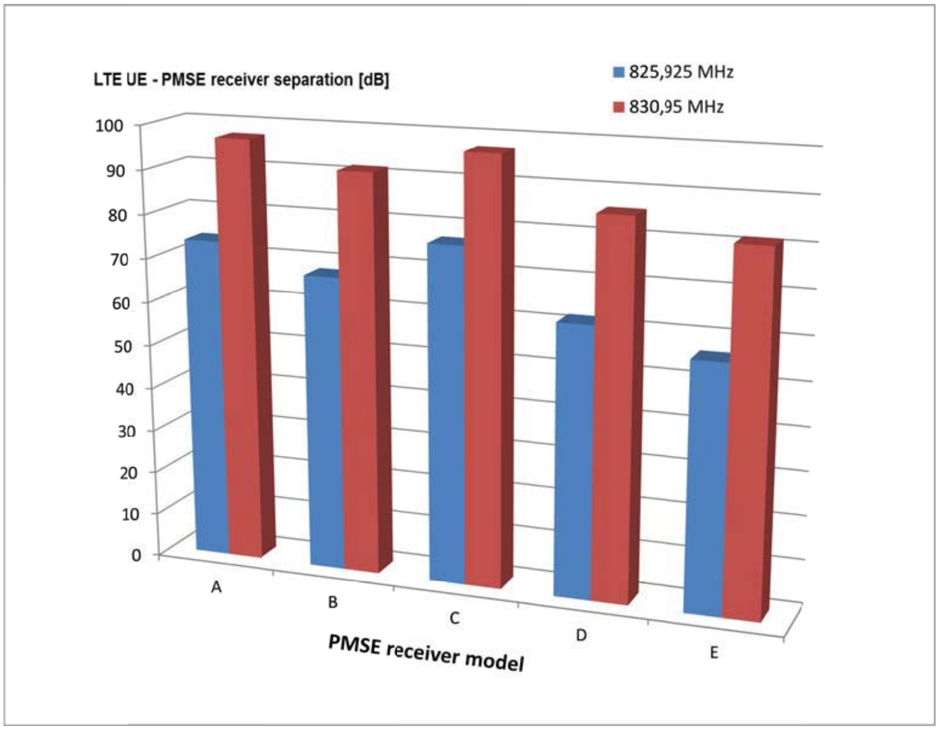

Figure 23: SINAD deterioration points for different PMSE receivers

During the measurements it had been observed that from time to time there were short drops in the SINAD even at high separation values. In order to determine whether or not this was a systematic effect a series of 100 measurements was taken under identical conditions. An analysis of the results showed that the distribution of SINAD values was Gaussian and that the variation in SINAD values was caused by random noise.

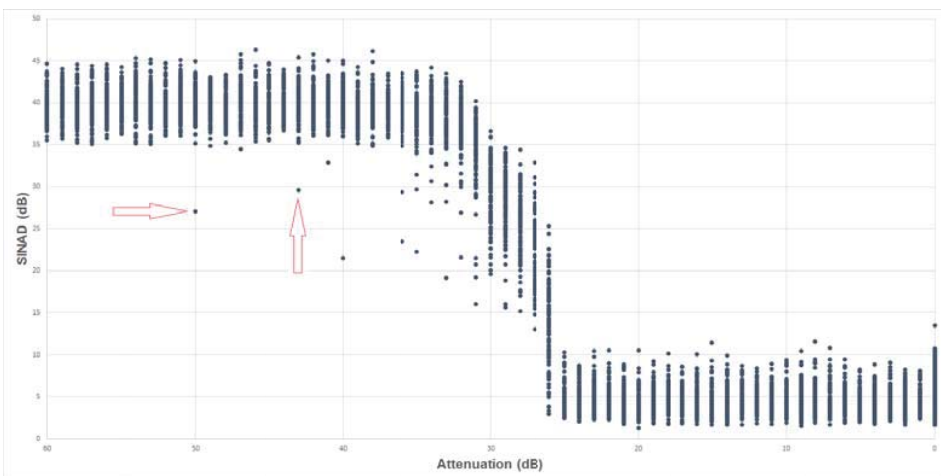

Figure 24: Distribution of SINAD values vs. path attenuation (the red arrows indicate anomalous measuring points)

Figure 25 shows the average and standard deviation for the computed SINAD at each attenuation point for the whole 100 measurements. At attenuation levels between 59 and 45 dB, where occasional spikes were detected, the average SINAD equals 40 dB, while the standard deviation equals 2 dB. It is interesting to note that these values are very similar for the whole range of attenuation, between 59 and 45, which is a first indicator that there is not a general trend within it. Moreover, if we assume the spikes to be caused by pure noise, the distribution of values should follow a Gaussian distribution. In such a distribution 99.7% of the values are spread within μ ± 3*σ, where μ is the average and σ is the standard deviation. For the 100 measurements performed, 99.67% of the points are within those limits and evenly spaced over the attenuation range. Thus we conclude that the main statistics on the range under study are consistent with those of a random noise.

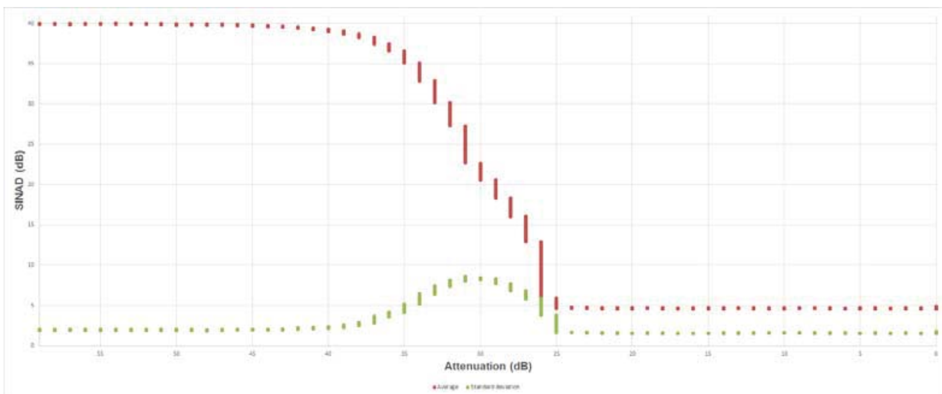

Figure 25: Average and standard deviation for each attenuation level

Impact of increased PMSE RF Signal-to-Noise Ratio

The previous measurements had been made at the minimum sensitivity level of the PMSE receivers at which a SINAD of 30 dB can be maintained, i.e. without any additional margin. To evaluate the behaviour of the PMSE systems when operating with some margin the RF output power, and thus the RF SNR were increased by 10, 20, and 30 dB over the sensitivity level. Figure 26 and Figure 27 show the SINAD curves for the combination of LTE UE 1 and PMSE receiver B operating at 830.950 MHz and 825.925 MHz, resp. Minimum separation values decreased as SNR increased; however, the relation is not strictly linear. An increase in SNR from 10 to 20 dB resulted in a reduction of the minimum separation of about 13 dB.

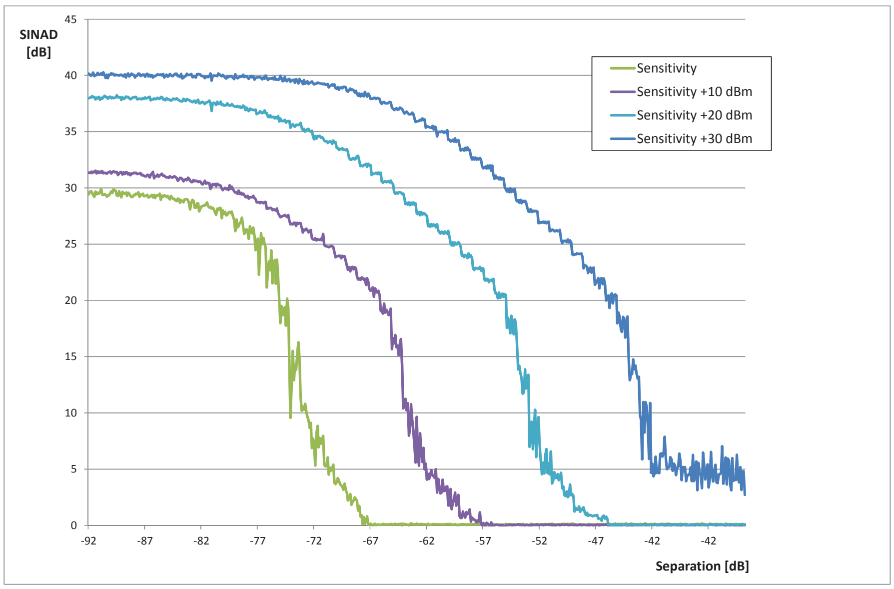

Figure 26: PMSE SINAD at 830.950 MHz

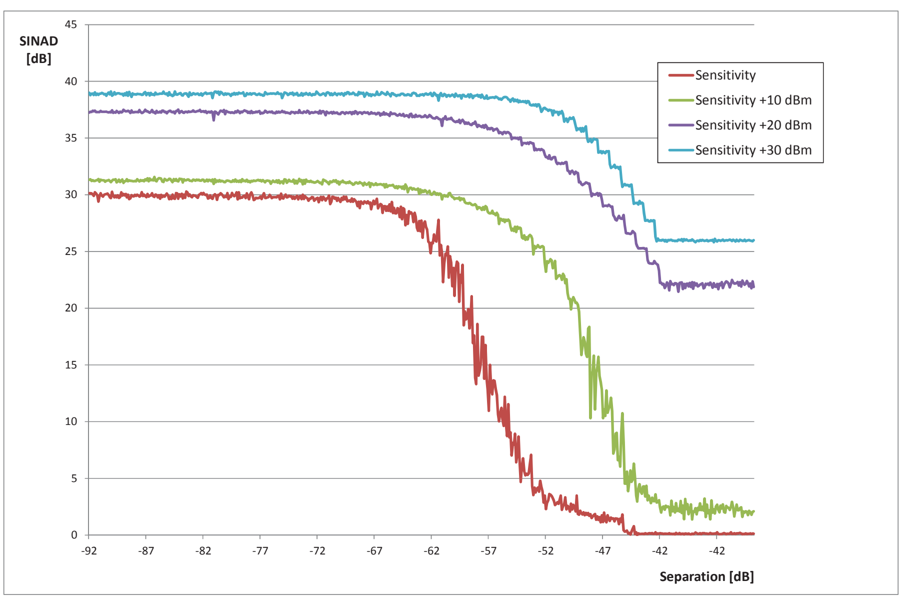

Figure 27: PMSE SINAD at 825.925 MHz

Overall, however, the increase in RF SNR (by 30 dB) and the decrease of the minimum separation were about equal (29.4 dB and 33.7 dB, resp., see Table 4).

	Minimum separation [dB]			
PMSE frequency	**825.925 MHz**		**830.950 MHz**	
FM Tx power level	**Absolute**	**Delta**	**Absolute**	**Delta**
Sensitivity	74,3	-	88,3	-
Sensitivity + 10 dBm	61,8	12,5	79,5	8,8
Sensitivity + 20 dBm	47,9	26,4	64,1	24,2
Sensitivity + 30 dBm	44,9	29,4	54,6	33,7

Table 4: Minimum separation vs. PMSE transmit power for LTE UE1 and PMSE receiver B

Handover measurements

For the handover measurements the path attenuation between LTE UE and PMSE receiver was varied as described above, and the RF and audio signals were recorded. At a predefined value of the variable attenuator A1 which corresponds to a certain LTE UL power level P_{thresh} seen by the LTE pico BS (and the PMSE receiver) the handover from LTE band 20 (800 MHz) to band 7 (2.6 GHz) was initiated (Figure 28). Measurements were made at the six defined PMSE frequencies and for various combinations of LTE UE and PMSE receivers. For each of these combination handovers were initiated at several different values of A1 which had been adapted to the PMSE RF frequencies.

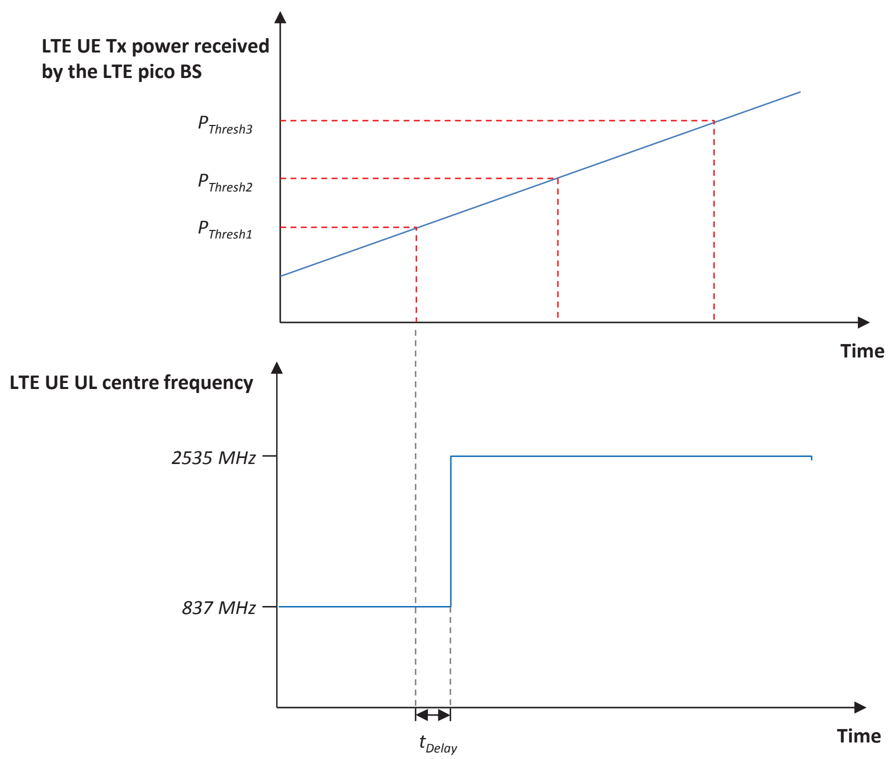

Figure 28: Simulated LTE inter-band handover mechanism

In the vast majority of cases the handover was completed in less than two seconds after initiation. There were a few cases, however, in which the handover took more than 20 seconds to complete. During the time available for the test event it could not be determined whether this delay was caused by the base station emulator or by the LTE UE.

In Figure 29 two exemplary SINAD curves are shown that were measured at 830.950 MHz and 827.950 MHz with the combination of PMSE receiver B and LTE UE 5. As the separation between LTE UE and PMSE receiver was reduced the SINAD decreased. At a certain separation value (68 dB for the 830.095 MHz signal and 61 dB for the 827.950 MHz signal) the handover was initiated, and the SINAD returned to its initial value of 30 dB. When the handover was initiated before the minimum separation was reached no deterioration of the SINAD could be observed.

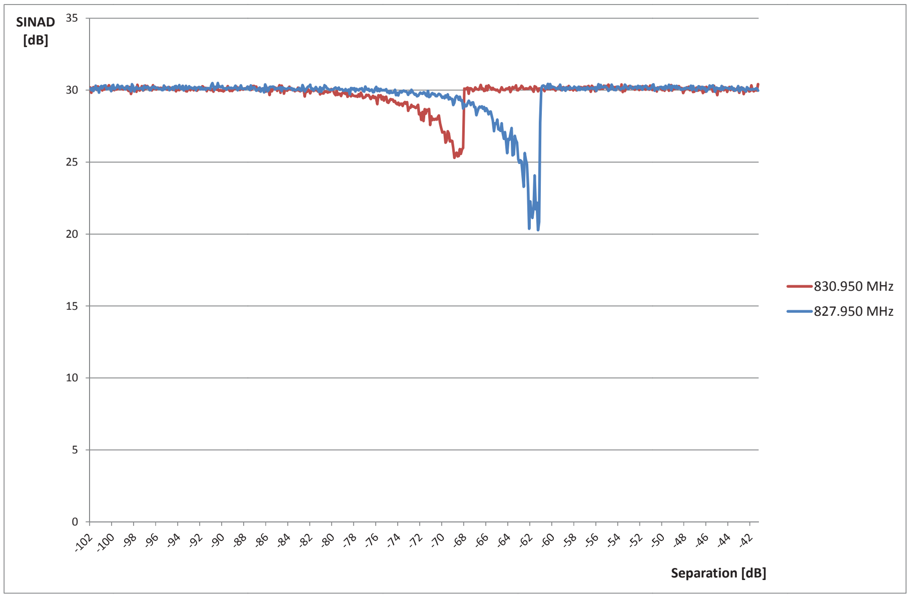

Figure 29: PMSE SINAD vs. separation between LTE UE and PMSE receiver, with LTE handover

During each test run the 821-832 MHz duplex gap spectrum was recorded. This band was later analysed offline for glitches or other artefacts that might have been generated in the course of the handover process and that could cause interference to PMSE signals. The power measured in the duplex gap before, during and after a handover is exemplarily shown in Figure 30. The integration time was 10 ms, equalling the length of one LTE frame. Typically, undershoots and a few spikes, all in the range of 0.1 dB, were observed but no signals with the potential to cause harmful interference to PMSE systems.

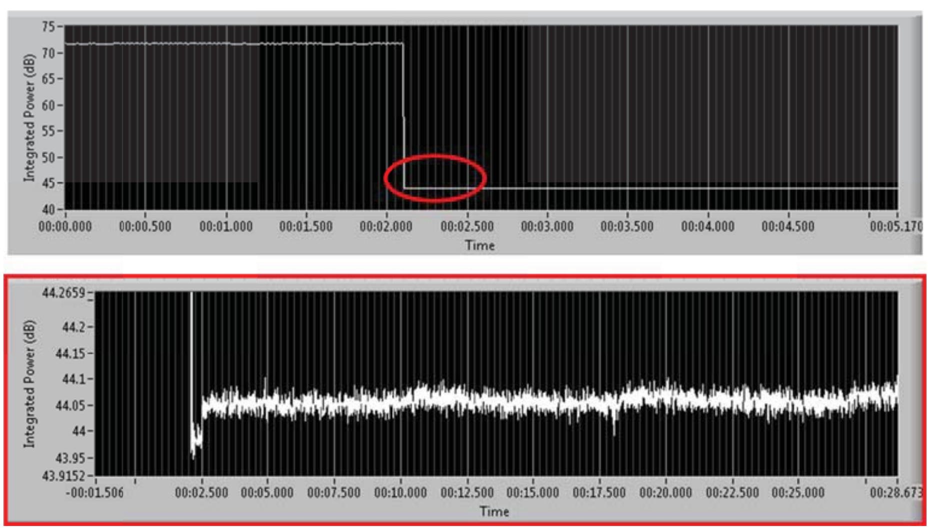

Figure 30: Power measured in the duplex gap (821-832 MHz) during LTE handover.

Start-up test

During the start-up test, an LTE UE was switched on in the presence of a strong 2.6 GHz LTE DL signal (representing a nearby pico BS) and a weaker 800 MHz LTE DL signal (representing a distant macro BS). The path attenuation between the LTE UE (model no. 1) and PMSE receiver (model B) was 47 dB, corresponding to a free-space distance of 6.43 m. The attenuation value was chosen to match that of the IRT measurements [4]. The audio output signal of the PMSE receiver and the 821-832 MHz duplex gap spectrum were recorded. In additional, the audio signal was monitored using a headphone.

Over a period of 60 seconds the device was switched on and off several times. After a few seconds the LTE UE reliably connected to the LTE pico BS, without any interference being audible other than the background noise described earlier which was always present, even in the absence of any LTE signal.

The off-line analysis of the RF power in the duplex gap revealed the presence of a periodic signal with a very low amplitude of less than 0.2 dB above the noise floor. This signal did not cause any audible or visible signal deterioration.

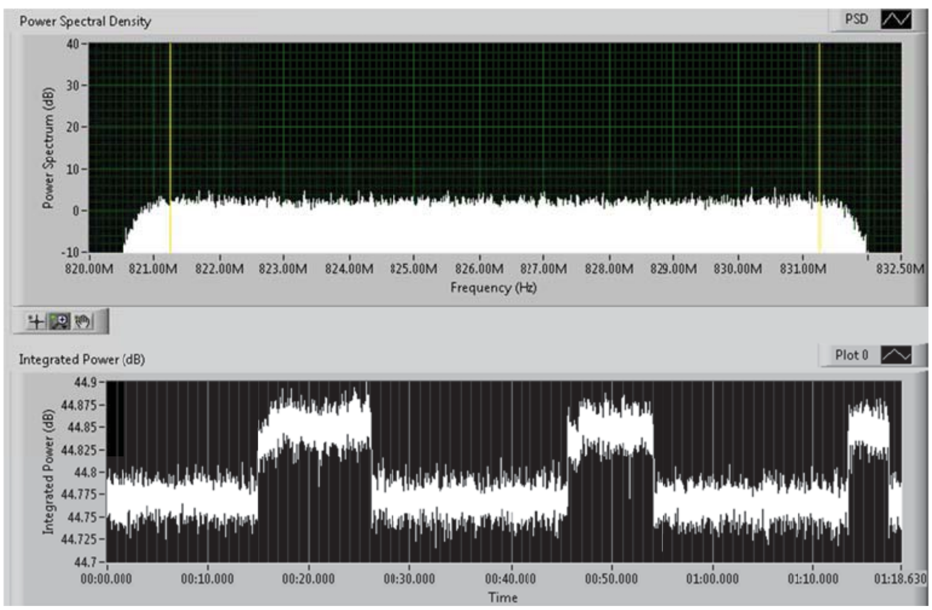

Figure 31: Power measured in the duplex gap (821-832 MHz) during LTE UE start-up.

LTE Picocell Deployment Considerations

This chapter reviews the PMSE protection requirements identified through the measurements and tries to connect them with the technical characteristics of LTE picocells. Its intention is to create a basis for further discussion and research work. Given the diversity of environments in which PMSE systems operate it would go beyond the scope of this report to provide a detailed analysis of the requirements or make recommendations for LTE picocell deployment.

PMSE protection requirements

The measurements yielded a range of values for the separation between PMSE receiver and LTE UE that is required to maintain a SINAD of 30 dB.

How these separation values translate into protection distances depends on the application environment which determines the path loss model that is to be applied. A comparison of the propagation curves of eight LOS and NLOS models is shown in Figure 32.

- ITU-R P.1238-7 [15] covers the range from 900 MHz to 100 GHz. The depicted curves show the path loss for the following conditions: 1) Near-LOS, indoor environment (parameters derived from [16]), transmitter and receiver on the same floor; 2) NLOS indoor (office) environment, transmitter and receiver on the same floor.
- WINNER II 3b NLOS is a model for indoor propagation / hotspots developed in FP7 project WINNER II [17]. Its application is limited to the 2-6 GHz frequency range and distances from 5-100 meters.
- The APWPT model [18] is defined specifically for PMSE systems and takes into account body loss.
- The IEEE 802.11 C model has been used to characterise indoor path loss between PMSE and LTE systems in the 1785-1805 MHz frequency range in ECC Report 191 [19]. The depicted curve shows the path loss for a breaking point of 5 m.
- WINNER II 3b LOS [17] is the line-of-sight version of the aforementioned indoor propagation model.
- The Extended Hata model [20] can be adapted to a variety of environments. The curve depicted below shows the path loss for a range of 0-100 meters under LOS conditions. It is therefore almost identical to the free-space path loss curve.
- The Free-Space path loss curve is calculated from the standard Friis formula.

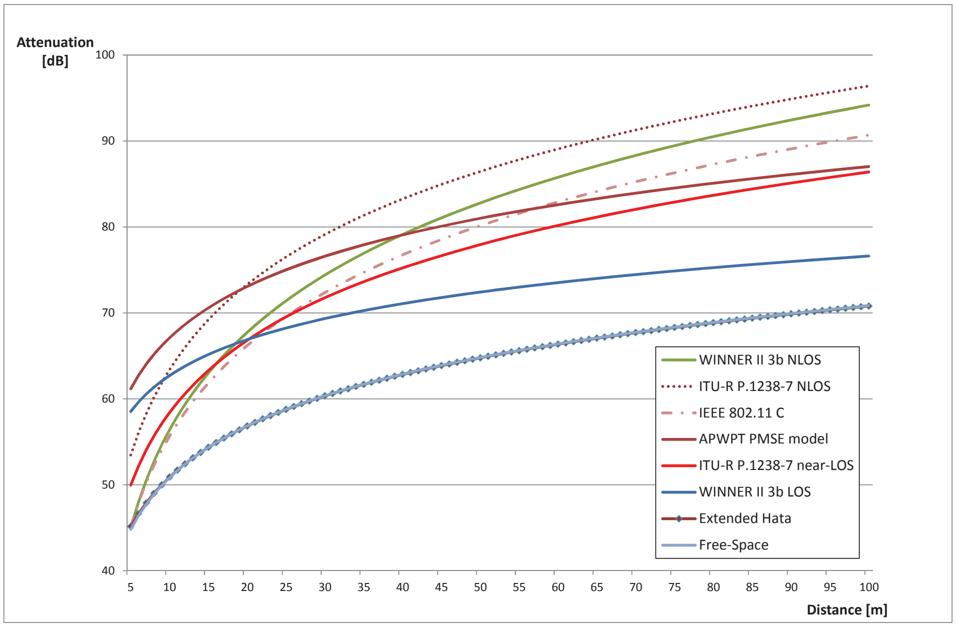

Figure 32: Comparison of path loss models

Exemplary calculations for protection distance for the tested PMSE system are shown in Table 5. The calculations were made for five different path loss models (LOS, near-LOS, and NLOS) and four different link scenarios.

'Worst case' and 'best case' refer to the highest and lowest minimum separation values identified during the measurements, with the PMSE receiver operating at its minimum sensitivity level. The other three scenarios consider an increase in RF signal SNR of 10, 20, and 30 dB, resp. which results in an about equivalent reduction of the minimum separation (see Table 4).

For PMSE systems operating at 830.95 MHZ, i.e. close to the LTE block edge, and at the sensitivity limit separation distances are relatively long, even under NLOS conditions. At 825.925 MHz, minimum separation distances are significantly shorter. At 830.95 MHz a PMSE system will have to operate with an additional signal margin of approximately 20 dB to achieve comparable minimum separation distances.

PMSE receiver operating at the sensitivity limit

PMSE frequency [MHz]	825.925		830.95	
Separation [dB]	Min.	Max.	Min.	Max.
	56.3	76.9	81.4	97.2
Minimum separation distance [m]	Best case	Worst case	Best case	Worst case
LOS	19	201	337	2.080
APWPT PMSE	3	31	52	323
ITU-R P.1238-7 near-LOS	8	46	66	243
IEEE 802.11C	10	41	54	154
ITU-R P.1238-7 NLOS	6	26	35	106

PMSE receiver operating at the sensitivity limit + 10 dB

PMSE frequency [MHz]	825.925		830.95	
Separation [dB]	Min.	Max.	Min.	Max.
	46.3	66.9	71.4	87.2
Minimum separation distance [m]	Best case	Worst case	Best case	Worst case
LOS	6	64	107	658
APWPT PMSE	1	10	16	102
ITU-R P.1238-7 near-LOS	4	20	29	107
IEEE 802.11C	5	21	28	80
ITU-R P.1238-7 NLOS	3	13	17	53

PMSE receiver operating at the sensitivity limit + 20 dB

PMSE frequency [MHz]	825.925		830.95	
Separation [dB]	Min.	Max.	Min.	Max.
	36.3	56.9	61.4	77.2
Minimum separation distance [m]	Best case	Worst case	Best case	Worst case
LOS	2	20	34	208
APWPT PMSE	0	3	5	32
ITU-R P.1238-7 near-LOS	2	9	13	47
IEEE 802.11C	3	11	15	41
ITU-R P.1238-7 NLOS	2	6	9	26

PMSE receiver operating at the sensitivity limit + 30 dB

PMSE frequency [MHz]	825.925		830.95	
Separation [dB]	Min.	Max.	Min.	Max.
	26. Mrz	46.9	51.4	67.2
Minimum separation distance [m]	Best case	Worst case	Best case	Worst case
LOS	1	6	11	66
APWPT PMSE	0	1	2	10
ITU-R P.1238-7 near-LOS	1	4	6	21
IEEE 802.11C	1	6	8	21
ITU-R P.1238-7 NLOS	1	3	4	13

Table 5: Minimum separation distances between PMSE receive rand LTE UE

LTE picocell coverage

Picocells are intend to provide wireless coverage in general, and high-speed broadband access in particular in 'difficult' areas which cannot be served adequately by macro base stations, such as densely populated areas, urban canyons, and indoor locations. For this reason, and as implied by the name, picocell coverage is typically small, in the range of 50 m.

Following is a simplified link budget calculation that relates the PMSE protection distances to the picocell coverage area.

The maximum output power of an LTE Pico BS (also referred to as Local Area BS [21]) is +24 dBm [16]. An LTE UE that is to transfer data at a speed of 2 Mbits per second requires a minimum received signal strength of -91 dBm [22]. The resulting maximum permissible path loss between a LTE pico BS and an LTE UE is 115 dB.

In Table 6 the required separation between PMSE receiver and LTE UE is compared to the picocell link budget. For the minimum and maximum PMSE frequencies that were measured the minimum separation distances are calculated, and the corresponding path loss at the LTE picocell frequency is determined. The upper table shows the calculation for a free-space/LOS scenario, the lower table for a NLOS scenario based on the ITU-R P.1238-7 model from [16].

Scenario: Free-space LOS

PMSE frequency [MHz]	**825.925**	**830.950**
Required separation (worst case) [dB]	77	97
Separation distance [m]	202	2.080
Corresponding path loss at 2535 MHz [dB]	87	107
LTE pico cell maximum path loss at 2535 MHz [dB]	115	
Margin [dB]	28	8

Scenario: ITU-R P.1238-7

PMSE frequency [MHz]	**825.925**	**830.950**
Required separation (worst case) [dB]	77	97
Separation distance [m]	46	243
Corresponding path loss at 2535 MHz [dB]	88	110
LTE pico cell maximum path loss at 2535 MHz [dB]	115	
Margin [dB]	27	5

Table 6: PMSE protection distances and corresponding path losses

In all four cases the resulting margin is positive which means that the picocell coverage area exceeds the PMSE protection range (Figure 33). As stated above these calculations are simplifications; in the ITU-R P.1238-7 scenario, for instance, shadowing and wall penetration losses have not been taken into account. It should therefore be understood that the conclusion from these calculations is not that with a single pico BS a PMSE system could be protected from LTE interference. With a typical capacity of up to 64 users one single pico base station would most probably not be sufficient for most events anyway. Furthermore, the maximum number of users is determined by the bandwidth allocated to each user and by the radio propagation and interference characteristics of the environment.

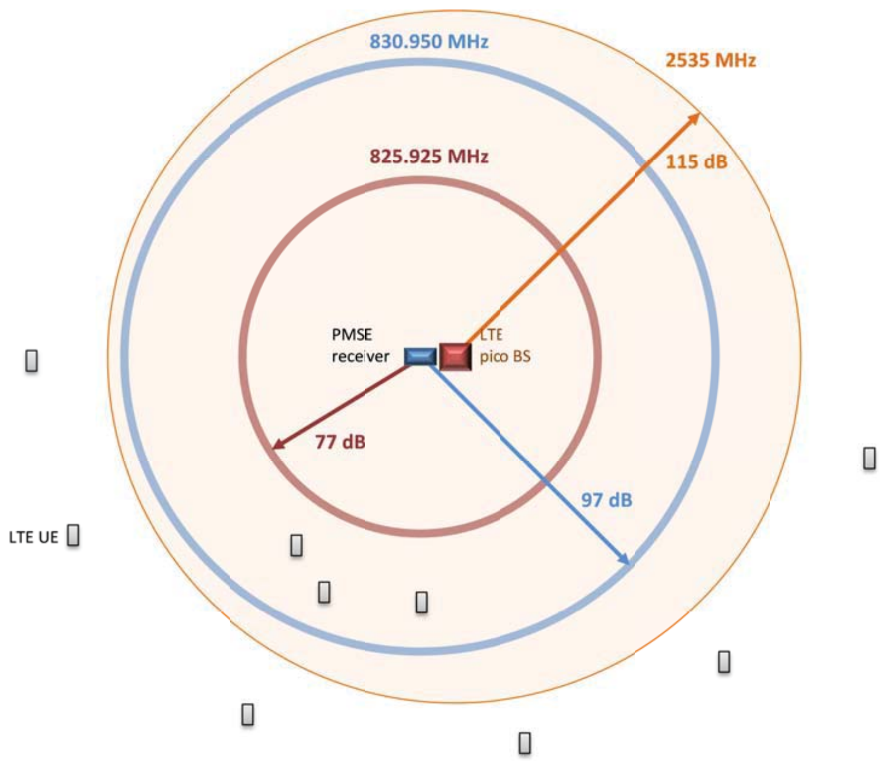

Figure 33: Simplified model of LTE pico BS coverage vs. PMSE protection ranges

It appears advisable to combine a deployment of LTE picocells with careful PMSE frequency and link budget planning. PMSE channels close to the LTE uplink block edge could be assigned to wireless links that have sufficient signal margin while the more critical links that may suffer from higher path loss, shielding and fading would be assigned to those channels further away from the LTE UL band. In this way, the risk of interference would be reduced even further. Alternatively, fewer LTE pico BS might be required to achieve a particular level of interference protection.

Summary and Conclusions

During the November 2013 PMSE-LTE coexistence measurements at the JRC premises in Ispra a total of five PMSE systems and seven LTE UE were tested. The findings of previous studies that LTE UE operating at 837 MHz can generate harmful interference to PMSE systems operating in the 821-832 MHz LTE duplex gap were confirmed. Minimum separations (protection ranges) between LTE UE and PMSE receiver were determined at which an acceptable audio quality (SINAD=30 dB) could be maintained by the PMSE system. The physical separation, i.e. the minimum distance between PMSE receiver and LTE UE at which no harmful interference occurs depends on a number of factors, most of all on the environment which determines the propagation characteristics, the PMSE channel frequency, and the PMSE receiver sensitivity. Consequently, the range of minimum separation distances is very wide; the values determined in this report range from 3 - 200 meters at 825.925 MHz to 35 – 2080 meters at 830.95 MHz (best case NLOS – worst case LOS).

Furthermore, the concept of LTE inter-band handover, from an 800 MHz macro cell to a 2.6 GHz picocell, as a potential interference mitigation technique was evaluated. The movement of an interfering LTE UE operating at 837 MHz towards a PMSE receiver was simulated, and at a certain point in time an inter-band handover was initiated. During each measurement run the audio and RF signals were recorded for later analysis. It was found that in the majority of cases the handover worked fast (within less than 2 seconds) and reliable. When the handover to the 2.6 GHz band occurred outside of the protection range of the PMSE system the SINAD was maintained without deterioration regardless of the distance between LTE UE and PMSE receiver. Before, during, and following the handover no signals with a potential to cause harmful interference and that could be attributed to the handover process were observed in the 821-832 MHz duplex gap.

A start-up test was conducted in which an LTE UE that was in the range of a distant 800 MHz macro base station and a nearby 2.6 GHz pico base station was switched on in the vicinity of a nearby PMSE receiver. The UE repeatedly and reliably connected to the pico BS within a few seconds after it was powered on. No interference to the PMSE signal could be observed during the entire process.

Finally, an 800 MHz and an 1800 MHz analogue PMSE system were operated in parallel with an LTE UE in close distance while the LTE system executed handovers from 800 MHz to 2.6 GHz and back. The audio signal of the 1800 MHz system was monitored for possible interference from cross-modulation. No interference could be observed.

In summary, the conclusions of this report are:

1. Deploying LTE picocells in combination with inter-band handover can avoid or reduce interference from active LTE UE to PMSE if handovers are executed outside the protection range of the PMSE receivers.
2. The deployment of LTE picocells operating in the 2.6 GHz band can avoid or reduce interference from multi-band LTE UE that are activated in the vicinity of a PMSE receiver.
3. As implementation aspects of the picocell and interband-handover concept were not part of the scope of this report further studies will be required to define LTE picocell deployment scenarios and respective requirements.

Annex A: Spectrum and OOB emissions of the tested LTE User Equipment

Maximum peak and average power are displayed.

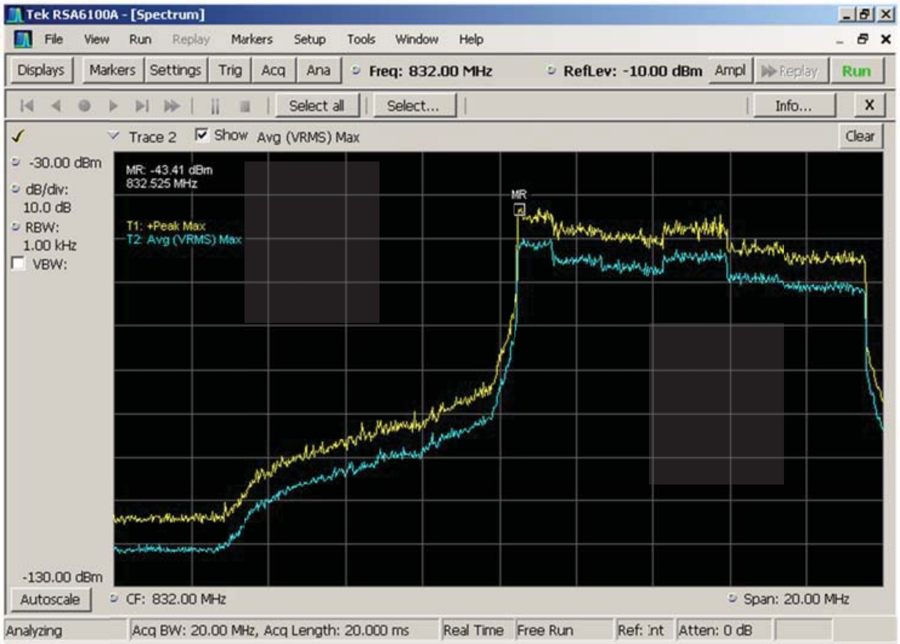

Figure 34: Spectrum of LTE UE #1 (USB modem)

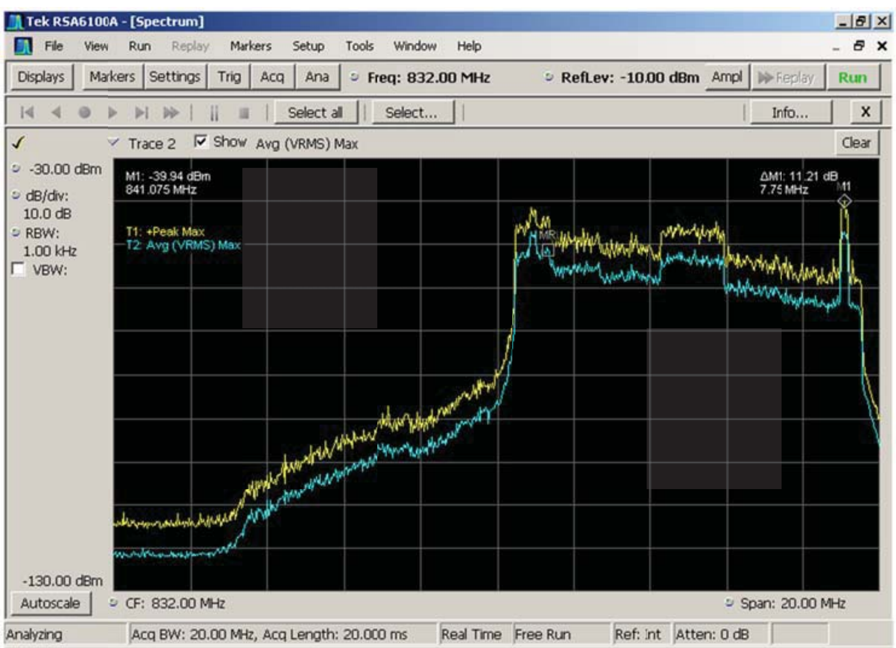

Figure 35: Spectrum of LTE UE #2 (USB modem)

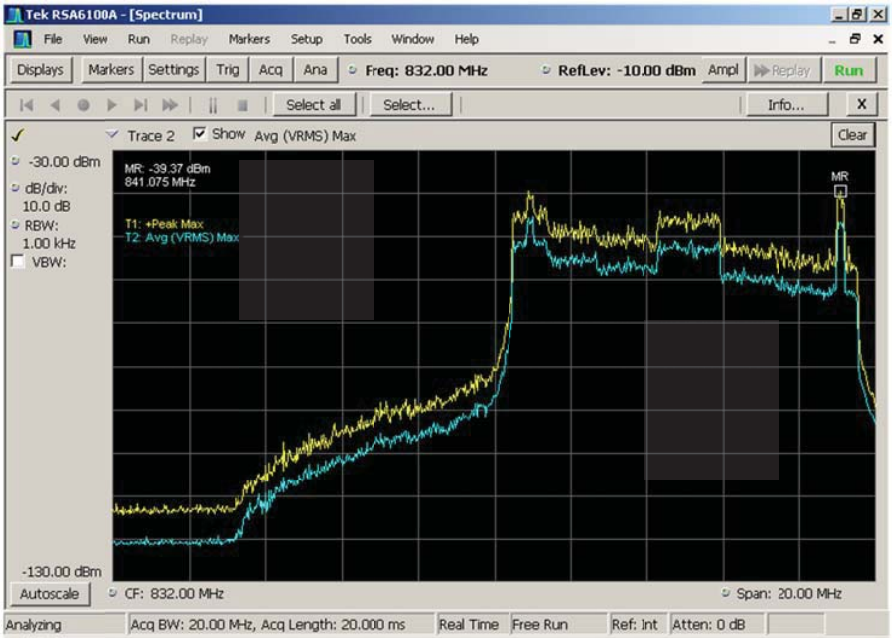

Figure 36: Spectrum of LTE UE #3 (USB modem)

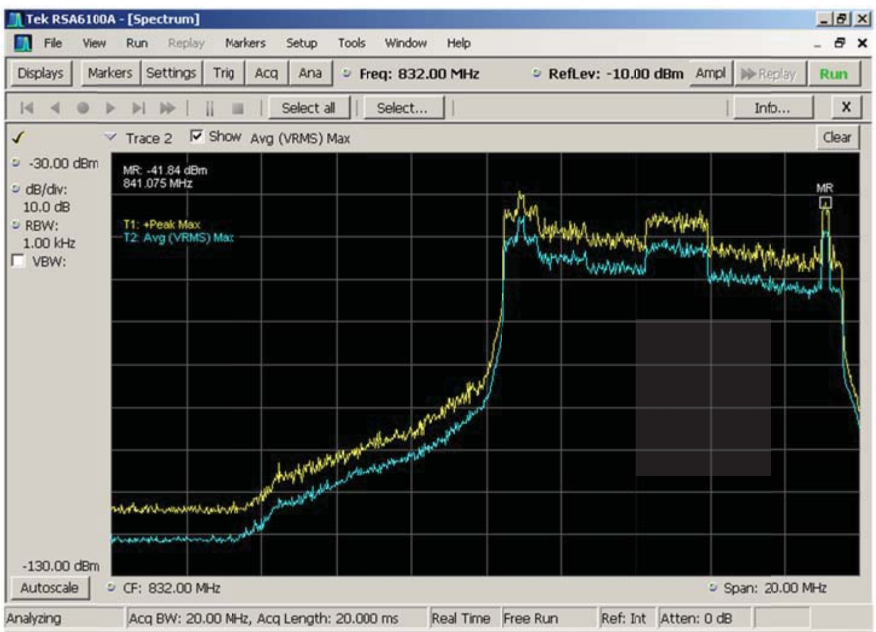

Figure 37: Spectrum of LTE UE #4 (USB modem)

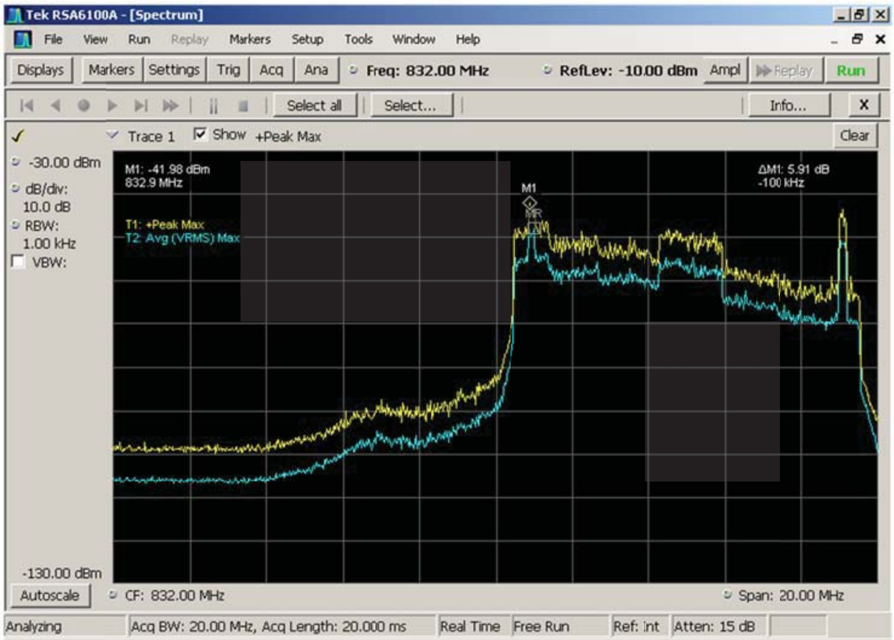

Figure 38: Spectrum of LTE UE #5 (Smartphone)

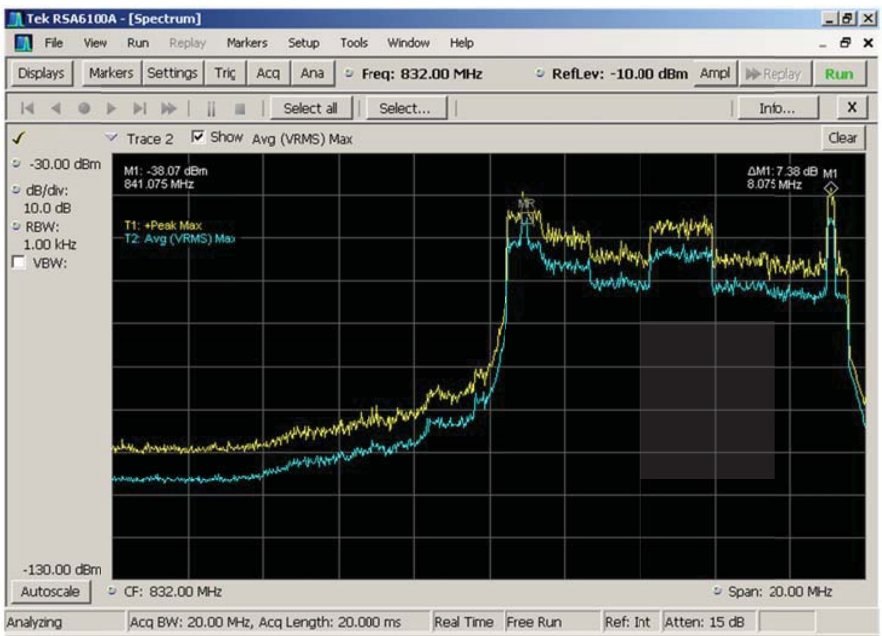

Figure 39: Spectrum of LTE UE #6 (Smartphone)

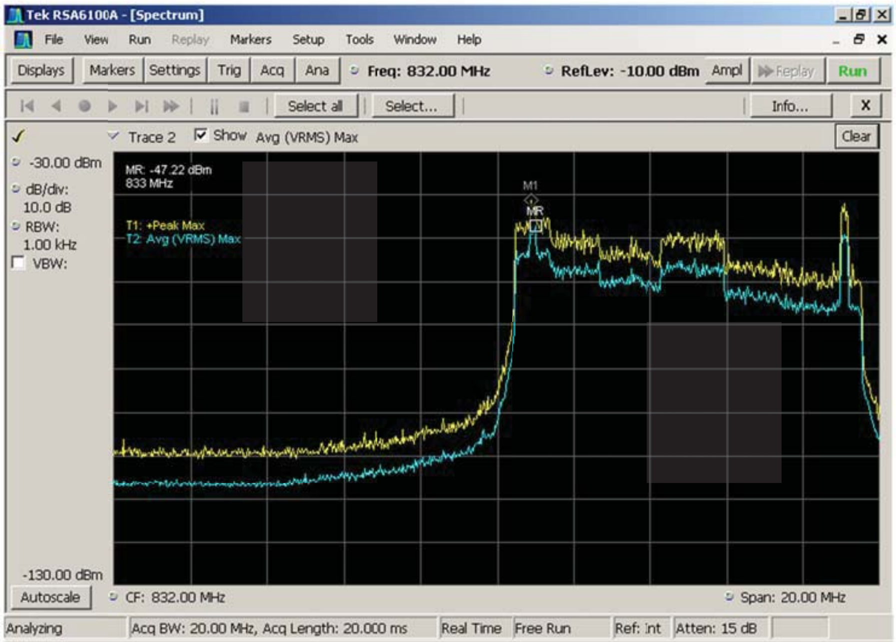

Figure 40: Spectrum of LTE UE #7 (Smartphone)

Glossary

Acronym	Meaning
ADC	Analogue-to-Digital Converter
APWPT	Association of Professional Wireless Production Technologies
BNetzA	Bundesnetzagentur
BS	Base Station
CEPT	European Conference of Postal and Telecommunications Administrations
DAC	Digital-to-Analogue Converter
dB	Decibel
dBm	Decibel milliwatt
DAS	Distributed Antenna Systems
DG CNECT	Directorate General for Communications Networks, Content and Technology
DKE	Deutsche Kommission Elektrotechnik Elektronik Informationstechnik
DL	Downlink
ECC	Electronic Communications Committee
ETSI	European Telecommunication Standards Institute
FDD	Frequency Division Duplex
FM	Frequency Modulation
GSM	Global System for Mobile communications
GSMA	GSM Association
HP	High-Pass
IRT	Institut für Rundfunktechnik
LP	Low-Pass
LTE	Long Term Evolution
LOS	Line Of Sight
NLOS	Non Line Of Sight
OFCOM	[UK] Office of Communications
OOB	Out-Of-Band
PMSE	Programme Making and Special Events
RB	Resource Block

RF	Radio Frequency
SINAD	Signal to Interference And Distortion ratio
SNR	Signal-to-Noise Ratio
SRD	Short Range Device
TBS	Transport Block Size
TBS idx	Transport Block Size index
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System

Table of Figures

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